Enhancing the environmental and economic sustainability of pig farming: The case of Brazil

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Abstract

Brazil is the fourth largest producer and exporter of pork in the world. Pig farming is raising environmental and economic concerns, mainly associated with the production and use of feed. It causes major environmental impacts due to its strong dependence on scarce resources (e.g. arable land, fossil fuel), and release of pollutants to the air, water and soil (e.g. greenhouse gases, nitrogen). Pig farming relies heavily on high quality food crops (i.e. cereals and oilseeds). In recent years, the growing competition for these high quality food crops with other sectors such as the energy and food sectors has resulted in rising feed costs. The problem of rising feed cost is worsened by price volatility of cereals and oilseeds. The use of alternative feed sources and the genetic improvement of pigs through selective breeding are expected to improve the environmental and economic sustainability of pig farming. The aim of this thesis was to assess the impacts of using co-products in the diets of pigs and of genetic improvement of pigs through selective breeding on both the environmental and economic sustainability of pig farming in Brazil. The results show that the use of co-products in the diets of pigs in Brazil raises feed costs, global warming potential, energy use, and excretions of nitrogen and phosphorus. However, it reduces land use. The use of co-products that can be produced on marginal land (e.g. macaúba cake) improves the efficiency of pork production when marginal land is not used to grow food crops. Breeders can use economic values that are derived by accounting for risk and risk preferences of farmers in order to produce breeding materials that increase the utility of risk averse farmers. Similarly, the mitigation of environmental impacts can be incorporated in breeding goals via using economic values that are derived by accounting for environmental costs. Genetic improvement of traits that raise farm productivity has the potential to reduce environmental impacts of farming while also raising the utility of risk averse farmers. The study also measured the effect of genetic expenses on dynamic productivity growth and its components using data from Dutch specialized dairy farms over 2007-2013. The results show that spending greater than the median expenses on genetics has the potential to increase productivity growth associated with inputs and investments in the first two years after the expenses.

Keywords: Bio-economic farm model, co-products, economic values, environmental impact, genetic improvement, input-specific dynamic productivity growth, life cycle assessment, macaúba kernel cake, pigs, risk aversion

Contents

Chapter 1

General introduction

1.1 Background

The world population is expected to reach 9.2 billion by 2050 according to the renowned projection of the United Nations Food and Agricultural Organization (FAO). From 2009 to 2050, agricultural output is required to increase by 70% in order to feed the global population during this period (FAO, 2009a). Livestock production, which is an integral part of the global economy with 40% of total agricultural output value (FAO, 2009b), is expected to play a leading role in achieving this target and in improving food security. The sector employs at least 1.3 billion people globally along the value chain (Thornton *et al*., 2006). Livestock production is a very important sector in the world economy and livelihood of people. This sector is, however, raising severe environmental and economic concerns in recent years. It causes major environmental impacts due to its strong dependence on scarce resources (e.g. cropland, fossil fuel and water), and release of pollutants to the atmosphere, soil and water (De Vries and De Boer, 2010; Steinfeld *et al*., 2006). Livestock production occupies about 75% of agricultural land (Foley *et al*., 2011) and accounts for about 15% of human-induced greenhouse gases (GHGs) emissions (Gerber *et al*., 2013) while covering only 33% of human protein consumption (Herrero *et al*., 2009). It also relies on high quality feed ingredients (cereals and oilseeds), which is inefficient from a food production point of view (Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a; Stehfest *et al*., 2009; Zhu and Van Ierland, 2004). The environmental impacts are expected to increase with the growing demand for animal protein that is expected to come from income growth, urbanization and population growth especially in emerging economies such as China, India and Brazil (Hume *et al*., 2011; Thornton, 2010). The global demand for meat is projected to increase by 73% between 2010 and 2050 (FAO, 2011). Eisler *et al*. (2014: 32-33) stated, “the increasing consumption of animal protein is generally considered at odds with Earth’s ability to feed its people”. Moreover, the growing human and livestock populations require increased production of food and feed, which causes increasing competition for arable land (i.e. the food-feed competition; Garnett, 2009).

Modern poultry and pig production systems rely heavily on cereals and oilseeds, which can also be used for direct human consumption. About one-third of global cereal production (equivalent to 1 billion tons annually) is fed to animals (Eisler *et al*., 2014). This has led to an increasing competition for feed ingredients with other sectors such as the energy sector and food sector (direct human consumption), and has resulted in increasing prices of food and feed ingredients. Following the increase in the prices of feed ingredients, feed costs are rising in recent years and as a result farm profits are shrinking (since farm output prices are not following suit). The economic problem is exacerbated by the volatility of prices of cereals and oilseeds in recent years. As producers are risk averse (Hardaker *et al*., 2015; Moschini and

Hennessy, 2001), uncertainty following from price volatility affects their investment, production and other farming decisions (Taya, 2012; Tangermann, 2011). Pannell (1999) stated that risk averse producers do not leap into large-scale adoption of novel technologies when facing considerable levels of uncertainty. Producers rather follow a small-scale trial approach, adjusting the scale of adoption either towards full adoption or towards disadoption on the basis of gained knowledge and experience about its effect.

Part of the land that is currently used for feed production can also be used for producing food crops for direct human consumption. Following the strong dependence of the livestock sector on arable land, debates are raised on how livestock should be produced (e.g. limiting it to marginal land, and the use of co-products and food waste as feed sources) in order to maximise food security. The competition for global arable land between crops used for food and feed can be reduced by shifting the use of food crops from the livestock sector to food sector for direct human consumption. Several studies documented that it is more efficient to use cereals and oilseeds for direct human consumption, rather than using them for animal feed as the conversion of plant food sources to animal food sources is inefficient (Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a; Stehfest *et al*., 2009; Zhu and Van Ierland, 2004).

The livestock sector can also reduce its (environmental and economic) impacts via genetic improvement of animals on top of other production- (e.g. use of alternative feed sources) and consumption-side (e.g. consumption shift from animal to plant food sources or within animal food sources from high impact to low impact products) mitigation strategies. Genetic improvement via selective breeding has been an important technology in improving productivity and efficiency of animal and plant production systems, by producing permanent and cumulative changes in performance. Van Middelaar *et al*. (2014), Bell *et al*. (2013) and Wall *et al*. (2010) for dairy, and Besson (2017) for fish farming systems show that environmental impacts can be reduced through selection for improved animal productivity and efficiency while improving economic performance.

1.2 Brazilian pig production

Brazil is the fourth largest producer and exporter of pork in the world next to China, European Union and United States with about 3.5 million tons of pork production in 2015 (ABCS, 2016). Brazil’s pork production has increased by about 32% between 2000 and 2015 (Figure 1.1). More than 90% of pork is produced in an intensive (industrial) pig production system, which is based on modern technologies using concentrated feed and high potential breeds (ABCS, 2016). In 2015, the breeding herd consisted of over 1.72 million sows, which produced more than 39.26 million pigs for slaughter (ABCS, 2016). About 24.4% of these breeding sows were located in Santa Catarina state followed by Minas Gerais with 15.9% (ABCS, 2016). Brazil’s pork consumption was growing from 1,040 thousand tons in 1995 to 2,986 thousand tons in 2015 (ABCS, 2016). The majority of production (about 85%) is used for domestic consumption. Per capita consumption increased from 13 kg in 2007 to 15.1 kg in 2015 (ABCS, 2016).

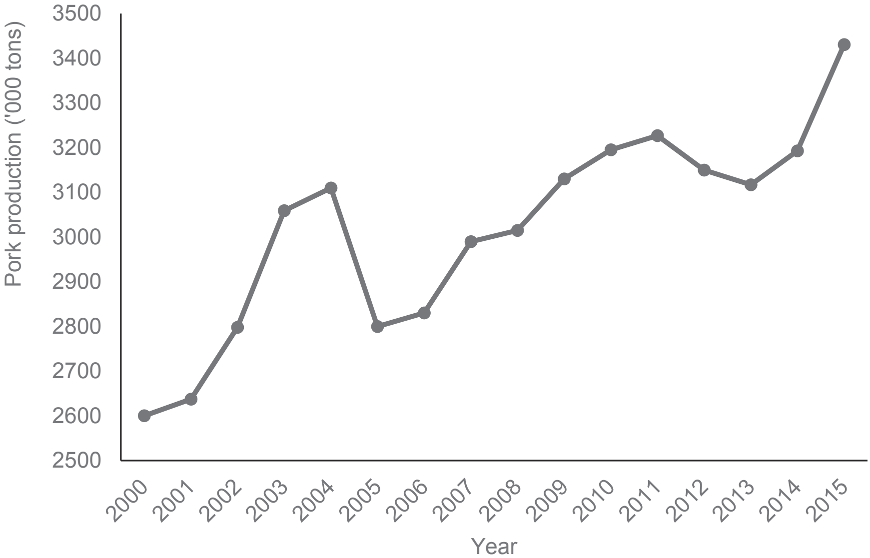

Figure 1.1 Evolution of Brazilian pork production over 2000-2015 (Source: ABCS, 2016)

Brazilian pig farming relies heavily on corn and soybean for feed (ABCS, 2016; Cherubini *et al*., 2015) and on imported pig breeds that are not tailored for local production conditions (e.g. tropical climate and market). In 2015, about 11 million tons of corn and 3.5 million tons of soybean meal were fed to pigs (ABCS, 2016). Following the strong dependence on high quality feed ingredients, pig farming is facing rising feed costs, and is causing environmental problems as described below in the 'Problem Statement' subsection. This thesis focuses on the contributions of alternative feed sources and genetic improvement of pigs in improving the economic and environmental sustainability of Brazilian pig farming.

1.3 Problem statement

Brazilian pig producers have faced rising and fluctuating feed costs in recent years (Embrapa Swine and Poultry Centre, 2017) due to price increases and price volatility of feed ingredients (Figure 1.2). Feed costs accounted for about 75% and 80% of the total cost of Brazilian pork production in 2015 and 2016, respectively (Embrapa Swine and Poultry Centre, 2017). Pig farming is also causing environmental problems such as emissions of GHGs, land and energy uses mainly associated with feed production and manure management (Cherubini *et al*., 2015). Innovations such as locally produced alternative feed sources using marginal lands and breeding programs better suited to local conditions (Wall *et al*., 2010; Kanis *et al*., 2005) might reduce the impacts of these problems on both economic and environmental sustainability.

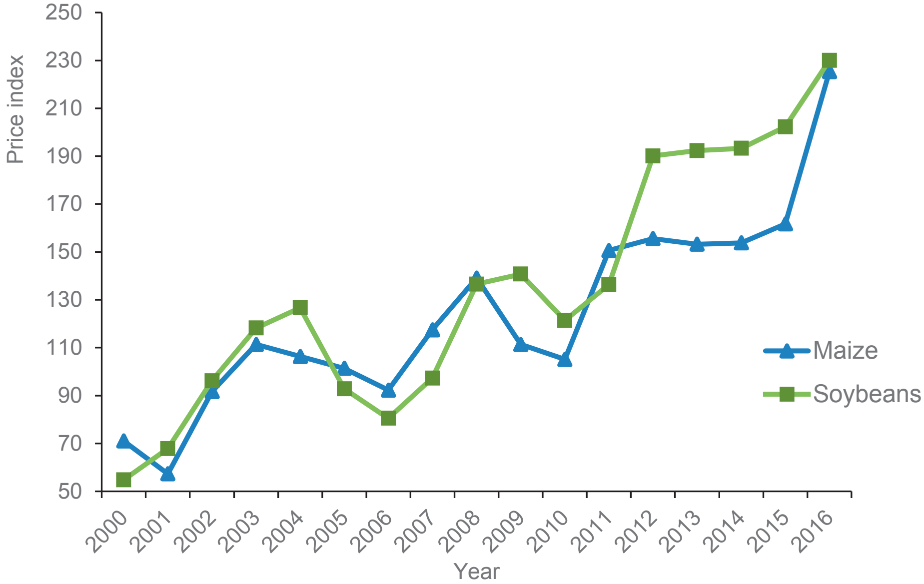

Figure 1.2 Producer price indices of maize and soybeans in Brazil (base year price: 2004-2006 average prices) (Source: FAO, 2018)

Feed production and manure management are the main hotspots of environmental problems in the pig supply chain (Groen *et al*., 2016; Cherubini *et al*., 2015; Van Zanten *et al*., 2015b; Nguyen *et al*., 2012). The production of feed ingredients in Brazil is associated with land use change (LUC), i.e. transformation of the Cerrado and rainforest areas into croplands for growing soybeans and corn, that amplifies emission of GHGs (Prudêncio da Silva *et al*., 2010). Transport of feed ingredients by trucks also raises transport cost and emissions since about 80% of pork production is located in the south and southeast regions (ABCS, 2013) whereas the production of soybean and corn is mainly concentrated in the Central West region (Santos Filho and Bertol, 2012). Several studies reported that the use of human inedible ingredients such as co-products from food and energy processing industries, and use of 'marginal land' for feed production, can reduce the environmental impacts of livestock farming (Röös *et al*., 2016; Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a; Van Zanten *et al*., 2015b; Elferink *et al*., 2008). Although the use of human inedible ingredients and marginal land for feed production may reduce the environmental impacts of farming systems, evidence on their effect on farm profitability is lacking in the literature. A feeding strategy (e.g. use of co-products) that reduces environmental impacts might negatively affect farm profitability. Therefore, the integration of environmental impact, land use efficiency and economic performance assessments is needed to complement existing literature on environmental impact assessment of pig farming. Furthermore, several studies have already explored the environmental impacts of using co-products in pig diets for Europe or North America (e.g. Mackenzie *et al*., 2016; Van Zanten *et al*., 2015b; Meul *et al*., 2012; Elferink *et al*., 2008). However, similar studies are not available for Brazil. Besides, the use of co-products is currently very limited in Brazil compared to in Europe and North America.

Bio-economic farm models (BEFMs) can be used to assess the effects of innovations on farm performance (Janssen and Van Ittersum, 2007). There are no generic BEFMs for assessing the effects of innovations on economic and environmental sustainability of pig farms. In pig farming, BEFMs have been limited to assessing the effect of genetic change of traits on farm profit (e.g. Serenius *et al*., 2008; Houška *et al*., 2004; De Vries, 1989), but have not been applied to evaluate the effects of innovations on environmental sustainability. BEFMs can be extended for this purpose by combining them with a life cycle assessment (LCA). LCA is an internationally standardized method to estimate the environmental impacts of a product throughout its life cycle (Rebitzer *et al*., 2004). Moreover, most existing studies (e.g. Houška *et al*., 2004; De Vries, 1989) followed a deterministic approach for system parameters, although some of the parameters in BEFMs are actually generated by a stochastic process (e.g. prices; Figure 1.2). Stochastic BEFMs are required to account for uncertainty (following from the variability of parameters) when exploring the effects of innovations. They can also easily be extended into utility functions (e.g. mean-variance) for assessing innovations from producers' utility point of view, thus also incorporating producers' risk preferences.

The emphasis of current pig breeding programs is on genetic improvement of production and productivity traits (e.g. litter size, growth rate and feed efficiency) using economic values (EVs) that are derived from simple profit equations or bio-economic models of risk neutral producers. This approach has two shortcomings. First, models that take risk into account provide better predictive power of producers' behaviour than those that do not. Since agricultural producers are risk averse (Hardaker *et al*., 2015; Moschini and Hennessy, 2001), risk and risk aversion need to be considered when deriving EVs. As EVs influence the magnitude and direction of genetic improvement in breeding objectives, the use of incorrect EVs (e.g. following from being derived from incorrect models) reduces selection efficiency and may wrongly affect the direction of selection (Cottle and Coffey, 2013; Smith, 1983). Second, as traditional breeding goals are defined solely in terms of traits that have economic importance, they ignore other socially desirable aspects (e.g. environmental sustainability), which are not valued in economic terms (Kanis *et al*., 2005; Olesen *et al*, 2000). Previous studies derived EVs of traits for dairy cattle (Wall *et al*., 2010) and beef cattle (Åby *et al*., 2013) by considering GHGs emission costs. So far, there are no studies that included both environmental costs and risk aversion into the estimation of EVs. Doing so will allow for defining sustainable pig breeding goals that improve both economic and environmental sustainability.

Brazilian pig farming relies on pig breeds that are not bred for local production conditions (e.g. markets, tropical climate). Hanenberg *et al*. (2010) reported that feed conversion is the most important trait in Brazil (compared with in other countries such as Netherlands, Germany and United States). By contrast, daily growth and litter size are less important in Brazil compared to, for example, in Germany where leanness of meat is the most important trait. As current Brazilian production is based on imported breeds from Europe and North America, identifying breeding goal traits with their respective EVs for the Brazilian pig production is key for improving its economic and environmental sustainability via genetic improvement.

Genetic improvement has been an important source of productivity growth in livestock production. The economics literature pays almost no attention to measuring the contribution of animal genetic progress to farm productivity growth. Only few studies (e.g. Atsbeha *et al*., 2012; Roibas and Alvarez, 2012; Roibas and Alvarez, 2010; Steine *et al*., 2008) measured the effects of genetic progress on productivity and profitability of dairy and beef farms. These studies, however, assumed that genetic level in the current period improves farm productivity or profit in the same period. This assumption is likely inaccurate since the return from current period genetic levels of dairy cows or bulls, for example, requires several years before to materialise, as the generation interval of cows is typically more than two years. Moreover, the effect of genetic progress on farm performance (e.g. milk production) is expressed over several years. Therefore, studying the effect of genetic progress on farm productivity and profitability requires a long term perspective.

1.4 Objective of the thesis

The main objective of the thesis was to assess the contributions of locally produced alternative feed sources and genetic improvement of pigs to enhancing both the environmental and economic sustainability of Brazilian pig farming. This was achieved by addressing the following five specific objectives:

1. To assess the environmental and economic impacts of utilising co-products in the diets of pigs;
2. To develop a stochastic bio-economic pig farm model to assess the impact of innovations on farm performance;
3. To derive economic values of pig breeding goal traits by taking into account environmental impacts and risk preferences of producers;

4. To assess the effect of using economic values of pig breeding goal traits that account for environmental costs and risk preferences of producers on response to selection; and
5. To measure the effect of genetic progress on farm level dynamic productivity growth and its components.

1.5 Outline of the thesis

The thesis is structured into seven chapters including this general introduction (Chapter 1) and general discussion (Chapter 7). The focus of the rest of the research chapters is as depicted in Figure 1.3. Out of the five chapters (Chapter 2 to 6), the applications of the first four chapters (Chapter 2 to 5) focus on Brazilian pig production. Chapter 6 focuses on Dutch dairy farming as panel data on Brazilian pig farming were not available for this research. Although data were not available on (Brazilian) pig farming, it is crucial to analyse the effects of genetic improvement on farm productivity growth and its components in order to generate information that helps in designing strategies and policies to improve farm performance and to maximise the contributions of breeding in enhancing farm performance. The implications of the (dairy farming) results for Brazilian pig farming are outlined in the general discussion chapter (Chapter 7).

Chapter 2 assesses the environmental and economic impacts of utilising co-products in the diets of pigs in Brazil. By employing the LCA technique, the environmental impacts (global warming potential, land and energy uses) of conventional and locally produced alternative feed ingredients were computed. Next, the environmental impacts of different diet scenarios along the feed production chain (from extraction of raw materials until its delivery at a pig farm) were estimated. Using the land use ratio technique, the opportunity cost (in terms of forgone human digestible protein from food crops) of using arable land for growing feed ingredients for producing pigs was calculated for the different diet scenarios. The cost-prices of the different diet scenarios were also documented.

Chapter 3 develops a stochastic bio-economic pig farm model for assessing the effect of different innovations on farm performance (private and social profits). By combining it with LCA technique, the model accounts for GHGs emission costs from feed production and manure management. It also takes into account the stochasticity of key economic and biological parameters. The model was used to assess the impact of using locally produced alternative feed sources (i.e. co-products) in the diets of finishing pigs on private and social profits of a typical Brazilian farrow-to-finish pig farm by constructing different diet scenarios.

Chapter 4 derives EVs of pig breeding goal traits. It proposes a method for integrating environmental costs and risk preferences of producers into the derivation of EVs of traits for improving both economic and environmental sustainability of pig farming at the same time. A breeding goal consisting of both sow efficiency and production traits is defined. A mean-variance utility function is then employed for deriving the EVs at finishing pig level assuming a fixed slaughter weight.

Chapter 5 presents the response to selection when EVs of breeding goal traits are derived by incorporating environmental costs and risk preferences of producers. The changing response from different EVs is illustrated for a breeding program with a separate dam- and sire-line. The breeding program supplied parents in a three-tier production system for producing crossbreds (fattening pigs) at commercial level. The effects from using the EVs that account for environmental costs and risk aversion on genetic gains of breeding goal traits, discounted economic returns and reductions in environmental impacts are determined by using the gene flow method.

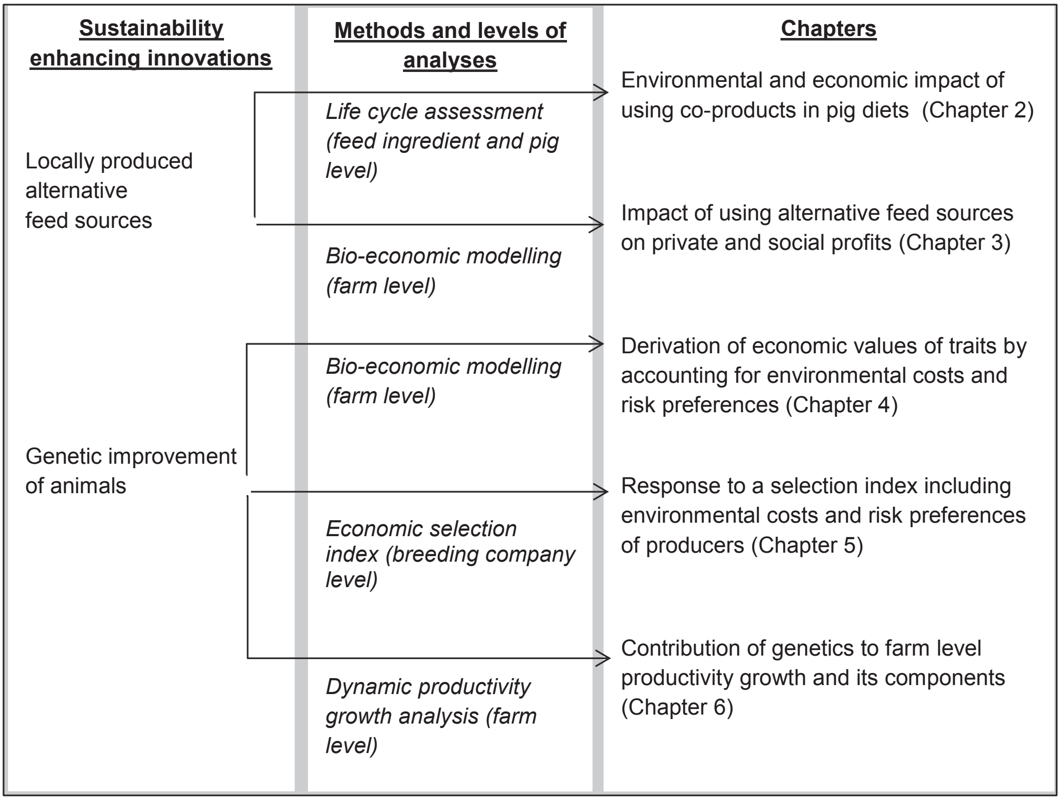

Figure 1.3 Outline of the thesis

Chapter 6 assesses the contribution of genetic progress to dynamic farm productivity growth and its components. Input- and investment-specific The Luenberger dynamic productivity growth indicator and its components were derived for Dutch specialised dairy farms using data over the period 2007-2013. The effect of lagged genetic level on farm productivity growth and its components was then measured using an impulse response analysis. This chapter focuses on dairy farming due to lack of farm level panel data for (Brazilian) pig farming, with information on genetic progress (e.g. total merit index, expense on genetics). However, the implications of the (dairy farming) results for Brazilian pig farming are outlined in Chapter 7.

Chapter 7 presents the synthesis of the main results of this thesis. Furthermore, it presents business and policy implications of the results. It also discusses potential avenues for future research. Finally, the main conclusions are presented.

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Chapter 2

Environmental and economic impacts of using co-products in the diets of finishing pigs in Brazil

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Abstract

Alternative feed sources are required to improve the environmental and economic sustainability of current pig production systems and to reduce the competition for cropland between the feed and food sectors. The objective of this study was to assess the environmental and economic impacts of utilizing existing and new co-products in the diets of pigs in Brazil. Three diet scenarios were designed: a reference scenario with a standard corn-soybean meal based finishing diet, a macaúba kernel cake based scenario and a co-product based scenario. The diets were equal in nutritional density. Inclusion of co-products in the diet of pigs has the potential to reduce the environmental impacts of pork production, particularly land use and the global warming potential when land use change is included. Compared with the reference scenario, land use per finished pig is 10% lower for the alternative scenarios. Global warming potential per kg live weight is 3.4-7.0% lower for the alternative scenarios when direct land use change is included whereas it is about 6-7% lower when indirect land use change is included. The land use ratio results (4.84 for the reference scenario and 4.35 for the alternative scenarios) imply that the production of pork using co-products can make available cropland for food crops production for direct human consumption. Compared with the reference finishing diet, the cost prices are 14% lower for the macaúba kernel cake and 5% lower for the co-product based finishing diets. The inclusion of co-products in the diets of pigs is, therefore, an important strategy to improve the environmental and economic sustainability of pig production.

Keywords: Co-products, macaúba kernel cake, pig diets, environmental impact, economic impact

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Abbreviations: SBM, Soybean meal; LUC, Land use change; GWP, Global warming potential; LU, land use; MKC, Macaúba kernel cake; RD, reference finishing pig diet; MD, Macaúba kernel cake-based finishing diet; CD, Co-product-based finishing diet; RD-S, Reference diet-based scenario (accounting for diets of sows, piglets, growing pigs and RD); MD-S, Macaúba kernel cake-based scenario (accounting for diets of sows, piglets, growing pigs and MD); CD-S, Co-product-based scenario (accounting for diets of sows, piglets, growing pigs and CD).

2.1 Introduction

Brazil is the fourth largest producer and exporter of pork in the world (USDA, 2014a). About 94% of the Brazilian pork production is based on intensive pig production systems using modern technology such as high potential breeds and concentrated feed (ABCS, 2016; Mariante *et al*., 2003). Pig production is highly dependent on concentrated feed derived mainly from corn and soybean (Cherubini *et al*., 2015; Santos Filho and Bertol, 2012), which can also be used directly as human food sources. Corn and soybean meal (SBM) account for more than 80% in the diets of pigs (ABCS, 2016; Santos Filho and Bertol, 2012).

The pig industry has been associated with both economic and environmental problems in recent years owing to its substantial dependence on corn and soybean. Economic problems follow from the growing competition between the use of soybean and corn as feed ingredients with the use for other purposes (e.g. direct human consumption). This has raised the prices of feed ingredients, and consequently increased feed cost. The Brazilian producer prices of soybean and corn increased by about 247% and 119% between 2000 and 2012, respectively (FAO, 2013). Feed cost accounted for more than 75% of the total cost of pork production in 2015 (Embrapa Swine and Poultry Centre, 2016).

Environmental effects follow from feed production and manure management. In the pork production chain, feed production is the largest contributor to environmental problems such as global warming potential (GWP), eutrophication, land use (LU) and energy use (Basset-Mens and Van der Werf, 2005; Cherubini *et al*., 2015; Groen *et al*., 2016). Pig production contributes to GWP through emission of greenhouse gases (GHGs) during cultivation, processing and transport of feed ingredients. The cultivation of feed ingredients in the Central West region of Brazil is associated with land use change (LUC), i.e. transformation of the Cerrado and rainforest areas into croplands which amplifies emission of GHGs (Alvarenga *et al*., 2012; Cherubini *et al*., 2015; Prudêncio da Silva *et al*., 2010). Transport distances of feed ingredients by trucks are substantial since about 80% of pork production is located in the south and southeast regions (ABCS, 2013) whereas the cultivation of soybean and corn has been expanding to the Central West and northeast regions (Santos Filho and Bertol, 2012). The LU problem follows from the competition for arable land worldwide between crops used for feed and food. About one-third of the global arable land area is used for animal feed production (Foley *et al*., 2011; Steinfeld *et al*., 2006). The conversion of plant food sources to animal food sources is inefficient relative to the direct consumption of plant food sources by humans (Stehfest *et al*., 2009; Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a; Zhu and Van Ierland, 2004). To improve LU efficiency, animal feed should, therefore, be produced without curtailing food crops production for direct human consumption. The use of inedible ingredients such as co-products from food and energy processing industries, and the use of 'marginal land' for feed production can help to increase the supply of food at lower environmental costs (Elferink *et al*., 2008; Röös *et al*., 2016; Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a).

In the literature, several options were suggested to reduce the environmental impacts (e.g. acidification, eutrophication, global warming potential, land use and energy use) of pig feed production. These include: (1) use of more locally produced ingredients (e.g. Eriksson *et al*., 2005; Meul *et al*., 2012; Van der Werf *et al*., 2005; Van Zanten *et al*., 2015b), (2) raising crop productivity via plant breeding, improving fertilization efficiency or crop rotation (e.g. Basset-Mens and Van der Werf, 2005; Meul *et al*., 2012; Van der Werf *et al*., 2005), (3) optimizing diet formulation (e.g. use of amino acids with low protein-diets; use of wheat based instead of maize based diet) (e.g. Cherubini *et al*., 2014; Eriksson et al., 2005; Garcia-Launay *et al*., 2014; Meul *et al*., 2012; Ogino *et al*., 2013), and (4) use of co-products (e.g. Elferink *et al*., 2008; Mackenzie *et al*., 2016; Meul *et al*., 2012; Van Zanten *et al*., 2015b). Focusing on the Brazilian situation, the use of co-products seems promising. Although there exist several studies that assessed the environmental impacts of using co-products in the diets of pigs in Europe and North America (e.g. Elferink *et al*., 2008; Mackenzie *et al*., 2016; Meul *et al*., 2012; Van Zanten *et al*., 2015b), similar studies are not available for Brazil and the use of co-products in Brazil is currently much more limited in comparison to Europe and North America. Even though large quantities of corn and SBM are produced within Brazil, the replacement of corn and SBM by more locally produced co-products and the use of marginal land for pig feed production may improve the LU efficiency and reduce emissions associated with LUC of the current Brazilian production system. Besides the use of conventional co-products such as wheat middlings, macaúba kernel cake (MKC) is emerging as a new co-product. MKC is a co-product that remains after oil extraction from the fruits of the macaúba palm which is mainly grown on marginal lands.

The objective of this study was, therefore, to assess generally, rather than for specific ingredients, the environmental and economic impacts of utilizing existing and new co-products in the diets of pigs in Brazil. The assessments of LU efficiency (i.e. the opportunity cost of using land for feed production) and economic performance complement existing studies on environmental impact assessment of feed production. Moreover, since Brazil is one of the world's top producers and exporters of feed and meat, an improvement in the sustainability of the Brazilian pig production system via the use of co-products will have a substantial effect on the sustainability of global meat production. The results of this study are useful for pig integrators (e.g. BRF) to improve the environmental and economic sustainability of their current production system.

2.2 Materials and methods

The environmental and economic impact calculations were started by defining three different finishing pigs' diets: a reference diet and two alternative diets. The rationale behind formulating the three diets is to assess the potential of using co-products in Brazilian pig production including macaúba kernel cake (MKC; refer to Subsection 2.2.1) and other existing co-products from the agro food and energy processing industries. The environmental and economic performance of the current system (corn-SBM based) is compared with co-product based alternative systems: 1) MKC based diet and 2) MKC in combination with other existing co-products. Corresponding to the three finishing pigs' diets, three scenarios were designed. The reference diet scenario (RD-S) represents a standard finishing pig diet in Brazil, formulated mainly from corn and SBM (Santos Filho and Bertol, 2012) in addition to considering diets for sows, piglets and growing pigs. The alternative two scenarios were formulated by partially replacing corn and SBM with only MKC, and replacing corn and SBM with MKC and existing co-products in the diets of finishing pigs. Local availability and expected land use advantage were the two criteria used to select co-products, resulting in the use of the following co-products: citrus pulp (dried), sugarcane molasses, wheat middlings and MKC (a new co-product). Scenario 2, MKC based diet scenario, contains MKC in the diet of finishing pigs and is referred to as MD-S. Scenario 3, referred to as CD-S, is a co-product based diet scenario containing MKC, citrus pulp (dried), sugarcane molasses and wheat middlings in the diet of finishing pigs. Before entering to the finishing phase to be fed one of the three finishing pig diets, pigs were assumed to be fed the same diets, i.e. diets for sows, piglets and growing pigs were similar for the three scenarios. Diets for sows, piglets and growing pigs were considered in the calculations of environmental and economic impacts since these diets were inputs to compute the land use ratio (see Subsection 2.2.4.3).

The rest of this section is structured as follows. The first subsection introduces macaúba and the study area Minas Gerais. This is followed by the presentation of the technical performance indicators of pig production in Brazil, which are the basis for computing the environmental and economic impacts of feed production. Then, the procedures for formulating the three diets for finishing pigs are discussed. This is followed by the presentations of the methods and data to determine the environmental and economic performances. Finally, a sensitivity analysis on selected parameters is presented.

2.2.1 Macaúba and Minas Gerais

The focus area of this study is Minas Gerais (MG), in the southeast of Brazil. It accounted for about 14% of the national pork production in 2012 (ABCS, 2013) and it was one of the top four corn producing states─ with an annual production of about 7 million tons in 2014 (IBGE, 2015).

Minas Gerais (and the southeast region in general) is known for its production of sorghum, sugarcane and citrus. It has also a significant potential for macaúba (*acrocomia aculeata*) production in existing pastures (Bhering *et al*., 2010).

Macaúba is a palm tree native to Latin America, and its fruits are used for oil production. It has a potential to produce up to 30 tons of fruits per hectare annually. The fruits have an oil content of 23-34% on dry weight basis (De Carvalho Lopes *et al*., 2011). The incorporation of macaúba in existing pastures results in an agroforestry system (Averdunk *et al*., 2012) without affecting the pasture yield (Villanueva *et al*., 2008). In the Brazilian Cerrado alone (which also covers part of MG), about 50 million hectares of pasture is available (INOCAS, 2012), most of which is suitable for macaúba production (INOCAS, 2012; Bhering *et al*., 2010). As a palm tree, macaúba can be cultivated on marginal land (Scariot *et al*., 1991) and can tolerate prolonged drought for up to six months (FAO, 1986).

Macaúba fruit has four components: epicarp, mesocarp (pulp), endocarp and kernel. The pulp and kernel are the two parts used for oil extraction. Macaúba cake, the co-product of oil extraction, is rich in essential nutrients for pig feed formulation (Costa Junior *et al*., 2015; Rodríguez Alderete and Valdez Ojeda, 2011). As the nutritional values of the kernel cake are better than those of the pulp cake, kernel cake is used in this study for the formulation of alternative diets. The crude protein (CP) and crude fibre (CF) contents of MKC are 18% and 41% on dry matter basis, respectively (Silva Junior, 2015). The chemical composition (organic matter, CP, CF, etc.) of MKC were taken from Silva Junior (2015). Amino acid composition of MKC is based on the pulp cake's composition corrected for the CP content (Costa Junior *et al*., 2015). Since MKC is an emerging co-product, the digestibility coefficients of its chemical constituents for finishing pigs are not yet documented in literature. Therefore, the digestibility coefficients of palm kernel meal (PKM) were adopted for MKC. Both PKM and MKC are co-products of oil extraction from palm trees. The chemical compositions (e.g. organic matter, CP and neutral detergent fibre contents) of PKM and MKC are comparable. Appendix 2.A1 provides the reason for using the digestibility coefficients of PKM based on the chemical compositions of both feed ingredients.

2.2.2 Description of production system

Brazilian pig production occurs mainly on intensive farms using modern technology such as high potential breeds and concentrated feed (ABCS, 2016; Mariante *et al*., 2003). Technical performance indicators of pig production in MG were obtained from agencies and scientific publications (Table 2.1). About 25 fattening pigs were finished for slaughter at 104 kg live weight (LW) per sow per year. About 267 kg feed is required to finish a pig: 42 kg for sow, 27 kg for piglets, 103 kg for growing pigs and 95 kg for finishing pig.

Table 2.1 Performance indicators of pig production adopted for pig production in Minas Gerais

Indicators	Unit	Value
Piglet production unit		
Piglets born alive [a]	#/sow/year	29.80
Weaned piglets [a]	#/sow/year	27.30
Average number of farrowing [a]	#/sow/year	2.40
Sow replacement rate [b]	%/year	37.50
Feed per sow (boar included) [b]	kg/sow/year	1,050.00
Feed per piglet raised to 23.7 kg [b]	kg/piglet	27.20
Growing-finishing unit		
Finished pigs [c]	#/sow/y	24.70
Slaughter weight [d]	kg	104.00
Final age [d]	days	147.00
Duration of the growing phase [d]	days	55.00
Duration of the finishing phase [d]	days	33.00
Feed intake in growing phase [e]	kg	103.00
Feed intake in finishing phase [d]	kg	95.00
Growth rate in finishing phase [d]	kg/day	1.02
Feed conversion ratio in finishing phase [d]	kg feed/kg gain	2.82

[a] Agriness (www.melhoresdasuinocultura.com.br). [b] Cherubini *et al*. (2015). [c] Embrapa swine and poultry centre (2016). [d] Adopted and calibrated from Rostagno *et al*. (2011). [e] Based on data from Rostagno *et al*. (2011) & Cherubini *et al*. (2015).

2.2.3 Pig diet composition

Pig production requires several feed types with different nutritional values according to the function and development stages of the pig. The Brazilian pig production system follows roughly a three phase feeding system: piglet (weaning to 24 kg body weight), growing (24-70 kg) and finishing (70-104 kg). Appendix 2A (Table 2.A2) presents the diet compositions of sows, piglets and growing pigs. The scenarios were only applied in the finishing phase for two reasons: first, most feed is consumed during that phase; second, finishing pigs have a better capacity to utilize co-products compared to piglets and growing pigs.

In this study, the diets of finishing pigs were formulated based on the Brazilian Table for Poultry and Swine (Rostagno *et al*., 2011) to meet the nutritional requirements of gilts (with standard performance) under *ad libitum* feeding. Table 2.2 shows the composition of these diets. All three diets contained 9.83 MJ net energy (NE) per kg and 7.80 g apparent ileal digestible lysine (AID LYS) per kg, which were required to achieve a growth performance as presented in Table 2.1. Furthermore, requirements of other amino acids relative to lysine were met: methionine

0.30, methionine + cysteine 0.59, threonine 0.71 and tryptophan 0.18 (Rostagno *et al*., 2011) and all diets contained 4 g/kg mineral and vitamin premix and 0.1 g/kg phytase (equivalent to 500 FTU phytase). To compose a diet that meets these requirements a commercial linear programming tool (BESTMIX®, Adifo, Belgium) was used which is a program that minimises the cost of a diet that meets a set of nutritional requirements. In Brazil the main feed ingredients are corn, SBM, amino acids and mineral supplements and therefore, we limited the options of possible ingredients to this list plus animal fat and the co-products which were used to formulate the alternative diets. Since we had limited the available ingredients in the program, price influences were minimal in the formulations.

Table 2.2 Diet composition for finishing pigs (% of kg product)

Ingredients (%)	Reference diet	Macaúba kernel cake-based diet	Co-product-based diet
Corn	69.76	64.71	47.35
Soybean meal	24.37	12.03	12.81
Macaúba kernel cake		20.00	10.00
Wheat middlings	4.00		15.00
Citrus pulp, dried			5.00
Sugarcane molasses			4.00
Animal fat		0.56	3.65
Mineral and vitamin premix	0.40	0.40	0.40
Monocalcium phosphate	0.32	0.52	0.38
Sodium bicarbonate		0.34	
Limestone	0.68	0.63	0.42
Salt	0.41	0.17	0.38
L-lysine	0.05	0.40	0.36
DL-methionine		0.12	0.11
L-threonine		0.11	0.13
Phytase [a]	0.01	0.01	0.01
Total	100	100	100
Nutritional values			
Net energy (MJ/kg) [b]	9.83	9.83	9.83
AID lysine (g/kg) [b]	7.80	7.80	7.80

[a] Equivalent to 500 FTU phytase per kg diet. [b] Net energy and apparent ileal digestible lysine based on CVB table 2011 (CVB, 2012).

The reference diet (RD, Table 2.2) mainly contains corn and SBM. In the MKC based diet (MD; Table 2.2) a fixed amount of 20% MKC was included following the recommendation of Costa Junior *et al*. (2015). Inclusion of more than 20% MKC can result in a lower nutritional value compared with RD, which might lead to a reduced feed intake and ultimately a reduced growth performance. In the co-product based diet (CD; Table 2.2) fixed amounts of 10% MKC, 15% wheat middlings, 5% citrus pulp (dried) and 4% sugarcane molasses were included. These inclusion levels are based on the recommendation of Rostagno *et al*. (2011) where co-products can be included in the diets of finishing pigs without compromising their performance (except for MKC). Due to the nutritional restrictions of the diets (i.e. 9.83 MJ/kg NE), the amount of MKC (20%) in MD is reduced to 10% in CD where the potential of using MKC together with existing co-products is explored. Therefore, three finishing diets were formulated for comparing the economic and environmental impacts of using new and existing co-products in the diets of pigs with the standard corn-SBM based system. Appendix 2A (Table 2.A3) provides the complete list of calculated nutrient contents of the diets.

2.2.4 Environmental impacts

The first part of this subsection presents the life cycle assessment (LCA) method which was used for computing the environmental impacts of the different diets. Then, the GWP of the diets with and without including emissions from LUC is presented. This is followed by the presentation of the land use ratio method as a tool for assessing the land use efficiency of feed sources. Finally, the cumulative energy demand (CED) as a measure of the direct and indirect energy uses is presented.

2.2.4.1 The life cycle assessment method

The LCA method was used to evaluate and compare the environmental impacts of the different diets. LCA is an internationally recognised and standardized method to estimate and evaluate the environmental impacts of a product throughout its life cycle (ISO 14040, 1997; Rebitzer *et al*., 2004). The method enables to evaluate the environmental performance of different alternatives and to identify hotspots (production stages with high impacts) in the production chain to improve the environmental sustainability of a production system (Wenzel *et al*., 2000). The LCA methodology is widely applied to assess the environmental impacts (e.g. global warming potential, acidification, eutrophication, land use and energy use) of livestock production such as poultry (e.g. Alvarenga *et al*., 2012; Prudêncio da Silva *et al*., 2014; Williams *et al*., 2006), dairy (e.g. Cederberg and Flysjö, 2004; Thomassen *et al*, 2008; Williams *et al*., 2006) and beef (e.g. Cederberg *et al*., 2009; Nguyen *et al*., 2010; Williams *et al*., 2006). It is also employed to assess the environmental impacts of pig production in general and pig feed production in particular (e.g. Basset-Mens and Van der Werf, 2005; Cherubini *et al*., 2015; Mackenzie *et al*., 2016, Ogino *et al*., 2013; Van der Werf *et al*., 2005; Van Zanten *et al*., 2015b). The four phases of LCA (i.e. goal and scope definition (including allocation procedures), life cycle inventory analysis, impact assessment and interpretation of results; ISO 14040, 1997) were followed to quantify the environmental impacts of Brazilian pig feed production as presented below.

The goal of this study was to assess the environmental impact of feed production that is required to finish a pig for slaughter. Feed production is the main contributor to GHGs emission in the pig production chain (Cherubini *et al*., 2015; Groen *et al*., 2016; Van Zanten *et al*., 2015b). The functional unit (FU) used was one finished pig with 104 kg LW at slaughter. The analysis covers extraction of raw materials (e.g. fertilizer, pesticide and energy), cultivation of crop ingredients, drying and processing of ingredients, manufacturing of concentrated feed and transportation in all stages until the pig farm as depicted in Figure 2.1. Emissions from housing, pig production, manure management, enteric fermentation and slaughtering were not considered as these were assumed to be similar across scenarios. Emission of GHGs from manure management and from enteric fermentation might be different among the scenarios due to the differences in the chemical compositions of the three finishing pig diets. Compared to RD, the alternative diets (MD and CD) contained lower levels of CP and higher levels of CF. The lower level of CP might result in lower nitrogen excretion (Canh *et al*., 1998) while the higher level of CF might increase methane emissions (Philippe and Nicks, 2015). We assumed that the lower emissions from nitrogen excretion offset the higher methane emissions. Moreover, a study by Van Zanten *et al*. (2015b) showed that diet composition (SBM vs rapeseed meal based growing-finishing pig diets) hardly affected GHGs emissions from manure management. Annual methane emission from enteric fermentation is 1.5 kg per fattening pig (IPCC, 2006). Enteric emission of monogasric animals is very small compared with ruminants (e.g. it is 0.2 million tons per year for pigs while it is 2.19 million tons for dairy cattle and 2.31 million tons for other cattle in western Europe; Steinfeld *et al*., 2006). Therefore, the differences in emission of GHGs from manure management and from enteric fermentation across scenarios were assumed to be negligible.

Economic allocation was used to allocate environmental impacts between the main product and co-products for products providing more than one output (e.g. soybean processing provides oil, meal and hulls). Economic allocation is the allocation of environmental impact among the main product and co-products based on their relative economic values (Guinée *et al*., 2004). Processing of 1 ton of soybean generates 706 kg SBM, 74 kg soybean hulls and 190 kg soybean oil (Vellinga *et al*., 2013). Using 2009-2013 average prices of US$411.6 per ton SBM and US$1008.4 per ton soybean oil (FOP prices, www.anec.com.br) and assuming that the price of soybean hulls is half of the price of SBM (206 US$/kg), SBM and soybean hulls account for 58.4% and 3.1% of the environmental impacts, respectively. For citrus pulp, wheat middlings, sugarcane molasses, animal fat and animal meal, the economic allocation coefficients of Vellinga *et al*. (2013) were used. For macaúba, all environmental impacts were allocated to the oil since the co-product is currently not traded in markets. However, this assumption was relaxed in the sensitivity analysis by assuming that MKC accounts for 5.4% of the environmental impacts of macaúba production and processing (refer to Subsection 2.2.6).

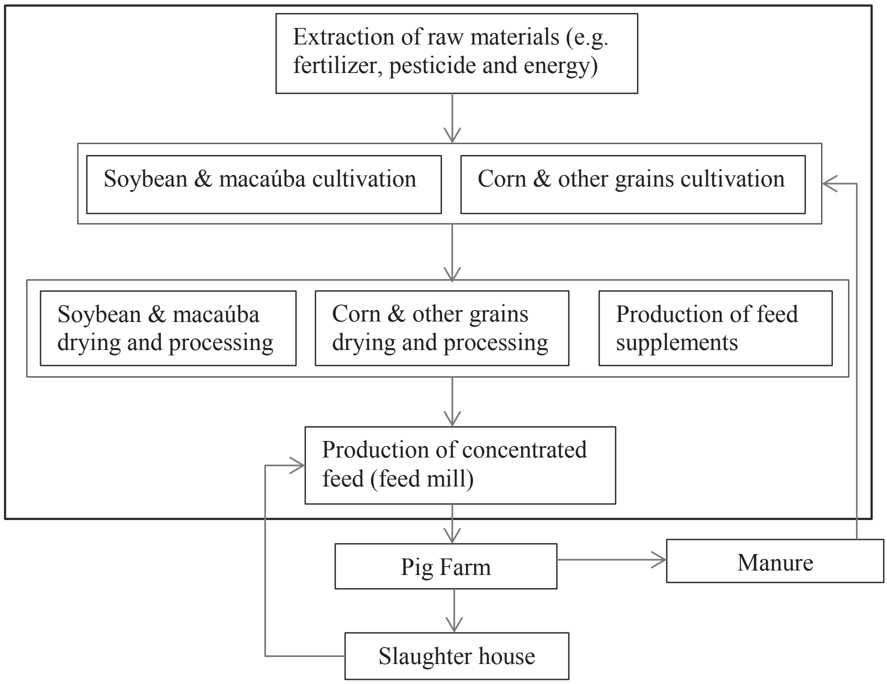


Figure 2.1 Flow-chart of pig feed production (arrows imply transportation)

Life cycle inventory data were based on literature sources. Life cycle inventory refers to the process of quantifying input requirements, emissions, wastes and other outputs for the entire life cycle of a product/process. We assumed that pig farms in MG obtain soybean from Central West region and other ingredients from within MG. Life cycle inventory data for corn cultivation were taken from Alvarenga *et al*. (2012) and for soybean from Prudêncio da Silva *et al*. (2014; 2010). Truck transport (16-32 tons) of 1350 km was assumed for delivering soybeans to a processing station in MG. Truck transport (16-32 tons) of 200 km was assumed for delivering corn to the feed mill. For feed milling (grinding and pelleting) values of 41 kWh of electricity and 20.5 kWh of natural gas per ton of feed were adopted (Garcia-Launay *et al*., 2014). Refer to Table 2.3 for the complete list of life cycle inventory data sources for each feed ingredients and processes.

Environmental impacts related to resource use (e.g. land and energy) and emissions to air (e.g. CO_2 and N_2O) were assessed. Three impact categories: global warming potential (GWP; kg CO_2-eq), land use (LU; m^2) and cumulative energy demand (CED; MJ) were assessed as the livestock sector significantly contributes to these categories (Steinfeld *et al*., 2006). The CML-IA Version 3.04 method (PRé Consultants, 2016), developed by the Centre of Environmental Science of Leiden University in the Netherlands, was used for characterising GWP. For LU, the ReCiPe Midpoint (H) Version 1.11 method (Goedkoop *et al*., 2013) was used. The CED was based on the method published by Ecoinvent version 1.0 and expanded by PRé Consultants (PRé Consultants, 2016). Simapro® 8 (PRé Consultants, Amersfoort, the Netherlands) was used for computing the environmental impacts while accounting for the Brazilian situation.

2.2.4.2 Global warming potential

GWP is the sum of GHG emissions which follows in this case from production of feed ingredients, transportation and processing of feed. The emissions are associated with the use of farm inputs, combustion of fossil fuel and transport. GHG emissions from LUC are also included separately. The three GHGs- carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were used to determine GWP. GWP is expressed in CO_2 equivalent (CO_2-eq) using weights of 1, 28 and 265 for CO_2, CH_4 and N_2O, respectively (assuming 100 years life span) (IPCC, 2015). Table 2.3 presents the GWP of the production and delivery of feed ingredients to a feed mill in MG, as well as the GWP of production and delivery of feed to a pig farm. The GWP of producing feed required for finishing a 104 kg LW pig was computed using the GWP of each feed ingredient (Table 2.3), technical performance of pig production (Table 2.1) and diet compositions of sows, piglets, growing pigs (Appendix 2A, Table 2.A2) and finishing pigs (Table 2.2).

Land use change (LUC) emission is one of the main sources of GHG emission in Brazilian feed production (Prudêncio da Silva *et al*., 2014; 2010). It refers to the conversion of land (e.g. forest and shrub land) into cropland for the cultivation of feed ingredients. Due to the variability and lack of consensus on the methods of calculating LUC emissions (Van Middelaar *et al*., 2013), both direct LUC (dLUC) and indirect LUC (iLUC) emissions were computed. Emissions from dLUC attribute to the specific crop cultivated on the transformed land. Emissions from dLUC were only included for products cultivated in the Central West region and not for the southeast region where deforestation took place more than 20 years ago (Prudêncio da Silva *et al*., 2014; 2010). Soybeans originate in the Central West region and therefore dLUC was included. In the Central West region, 1% and 3.4% of the land used for soybean production is assumed to be transformed from tropical rainforest and the Cerrado, respectively (Prudêncio da Silva *et al*., 2010). Emissions per hectare are 825 tons CO_2-eq for tropical rainforest and 297 tons CO_2-eq for the Cerrado (Van Middelaar *et al*., 2013). An amortization period of 20 years was used to calculate the annual emissions. Using the economic allocation rates, the dLUC emissions (kg CO_2-eq/kg product) are 0.33 for SBM, 0.81 for soybean oil and 0.17 for soybean hulls. According to the iLUC approach, every area of land used for commercial production is responsible for total LUC following the globalisation of feed and food markets (Audsley *et al*., 2009). When demand for one or more feed ingredients increase, the production of these ingredients require additional cropland and might result in the displacement of other crops somewhere in the world. The displaced crops might be cultivated on land that is converted from other form of land use (e.g. forest), causing iLUC. The value proposed by Audsley *et al*. (2009) (1430 kg CO_2-eq per hectare of agricultural land) was used to compute emissions from iLUC. Audsley *et al*. (2009) computed this emission factor by dividing the total worldwide GHG emissions from LUC in 2004 by the total amount of agricultural land in the same year.

2.2.4.3 Land use efficiency

The land use ratio (LUR) method developed by Van Zanten *et al*. (2015a) was adopted to measure land use efficiency of feed sources. The LUR quantifies the trade-off between the use of land for producing food crops for direct human consumption and feed for animals. Since the ultimate goal of food production is to provide sufficient food for humans from plant or animal food sources, the most efficient food source is the one that requires the lowest area of land for a given level of food production.

In this study, LUR is defined as the ratio between the maximum amount of human digestible protein (HDP) which could be derived from food crops on the land used to produce the feed required to finish one pig and the amount of HDP from one pig. Mathematically,

$$LUR = \frac{\sum_{i=1}^{n}\sum_{j=1}^{2}\left(LO_{ij} * HDP_j\right)}{HDP_{pig}} \quad (2.1)$$

where LO_{ij} is the land use/occupation (m^2) to produce feed ingredient i ($i = 1, \ldots, n$) in region j (j=Minas Gerais, Central West) which is required to finish one pig, HDP_j is HDP of food crops cultivated on the land used for feed production in region j and HDP_{pig} is HDP from one finished pig. A value of $LUR > 1$ implies that the use of land for pig feed production is inefficient since the HDP from using the land for food crop production is higher than HDP_{pig}; and a value of $LUR < 1$ implies that the use of the land for pig production is more efficient compared to using it for food crop production. HDP is selected as an indicator of nutritional value of food as meat mainly provides protein to humans (Van Zanten *et al*., 2015a). Four steps were followed to compute LUR.

Step 1. Quantification of the land area occupied (LO_{ij}) to cultivate the amount of each feed ingredient in the two regions (MG and Central West) that are needed to finish a 104 kg LW pig. Table 2.3 presents the land occupation (m^2/kg) for each feed ingredient. Given the land occupation (m^2/kg) for each feed ingredient (Table 2.3), technical performance of pig production (Table 2.1) and diet compositions of sows, piglets, growing pigs (Appendix 2A, Table 2.A2) and finishing pigs (Table 2.2), land area occupied to produce feed for finishing a

104 kg LW pig was computed (Appendix 2A, Table 2.A4). This occupation is based on a weighted average of feed required for sow, piglets, growing pigs and finishing pig.

Step 2. Assessing the suitability of each land area occupied (LO_{ij}) to grow food crops for direct human consumption. We assumed that all land occupied to produce feed ingredients is suitable to produce food crops (Table 2.4) except the land used for macaúba production. For mineral and amino acid supplements, zero land use is assumed. For the co-products, land use is allocated according to their economic allocation rates. In the sensitivity analysis, the land used for macaúba production was also assumed to be suitable for food crops production.

Step 3. Determination of the maximum HDP_j from cultivation of food crops on the suitable occupied land. HDP_j was computed for major food crops: soybean, wheat, corn, rice, potato (sweet and white) and cassava. These food crops are commonly grown in MG and Central West of Brazil. Table 2.4 presents the average yields of these crops and the total harvested area. The HDP of food crops per hectare is calculated using the average yields of crops (Table 2.4), the dry matter and protein contents (Table 2.5), and the protein digestibility of crops (Table 2.5). The crop with the highest HDP is selected for HDP_j. The HDP of the food crops, which are grown in MG and Central West, are given in Table 2.6. In both regions, soybean provides the highest HDP per hectare of land. Therefore, HDP_j refers to HDP of soybean in both regions.

Step 4. Computing the amount of HDP_{pig}. The HDP of a pig is calculated using the live weight at slaughter (i.e. 104 kg), kg edible product per kg slaughter weight, protein content and protein digestibility of pork (Table 2.5). Hence, HDP_{pig} equals 9.84 kg.

Table 2.3 Global warming potential (GWP; kg CO_2-eq/kg), land use (LU; m^2/kg) and cumulative energy demand (CED; MJ/kg) of producing and delivering a kg of feed ingredient at a feed mill in Minas Gerais

Ingredients	GWP	LU	CED	Sources of life cycle inventory data
Corn	0.367	1.762	4.114	Cultivation, drying and storage; and distance between cultivation and drying (Alvarenga *et al*., 2012; Prudêncio da Silva *et al*., 2014); and assuming 200 km distance between drying and feed mill
Soybean meal	0.634	3.591	7.929	Cultivation (Prudêncio da Silva *et al*., 2014; 2010); drying, storage and processing; and distance between cultivation and drying (Alvarenga *et al*., 2012); and assuming 1350 km distance between drying and processing; and 50 km between processing and feed mill
Soybean oil	1.547	8.971	19.262	
Soybean hulls	0.324	1.772	4.054	
Macaúba kernel cake	0.020	0.000	0.284	Data on cultivation, drying, storage, processing & distance among cultivation, drying and processing are not required following the zero economic allocation; and assuming 200 km distance (processing – feed mill)
Maize gluten meal	0.146	1.730	1.915	Cultivation, drying, storage and processing (IBGE, 2013; Agri-footprint database; Vellinga *et al*., 2013); and assuming 50 km distance between processing and feed mill
Rice bran meal	0.269	0.375	1.748	Cultivation, drying, storage and processing (IBGE, 2013; Agri-footprint database; Vellinga *et al*., 2013); and assuming 200 km distance between processing and feed mill
Wheat middlings	0.291	1.745	10.434	Cultivation (ecoinvent V3); drying, storage & processing (IBGE, 2013; Agri-footprint database; Vellinga *et al*., 2013); and assuming 200 km distance between processing & feed mill
Citrus pulp, dried	0.573	0.000	10.124	Cultivation, drying, storage and processing (Vellinga *et al*., 2013); and assuming 200 km distance between drying and feed mill
Sugarcane molasses	0.139	0.193	1.864	Cultivation, drying, storage and processing (Vellinga *et al*., 2013); and assuming 200 km distance between processing and feed mill
Animal meal	0.545	0.000	5.967	Assuming similar processing as in Europe (Agri-footprint; Vellinga *et al*., 2013) but adapted to Brazilian situation; and assuming 50 km each for distance (slaughter house - processing and processing - feed mill)
Animal fat	1.393	0.000	15.185	
Mineral & vitamin premix	0.640	0.000	9.050	Prudêncio da Silva *et al*. (2014)
Dicalcium phosphate	1.250	0.000	14.580	Prudêncio da Silva *et al*. (2014)
Monocalcium phosphate	1.170	0.000	17.700	Garcia-Launay *et al*. (2014)
Sodium bicarbonate	1.090	0.000	20.030	Prudêncio da Silva *et al*. (2014)
Limestone	0.040	0.000	0.760	Prudêncio da Silva *et al*. (2014)
Salt	0.200	0.000	2.930	Prudêncio da Silva *et al*. (2014)
L-lysine	4.300	0.000	119.20	Garcia-Launay *et al*. (2014)
DL-methionine	3.050	0.000	90.900	Garcia-Launay *et al*. (2014)
L-threonine	4.300	0.000	119.20	Garcia-Launay *et al*. (2014)
Phytase	1.900	0.000	26.000	Garcia-Launay *et al*. (2014)
Feed milling	0.011	0.000	0.160	Garcia-Launay *et al*. (2014)
Transport (Mill - Farm)	0.004	0.000	0.050	Assuming 35 km distance between feed mill and pig farm

Table 2.4 Average yield (kg/ha) and total harvested area (1,000 ha) of food crops in Brazil in 2013 (IBGE, 2015)

	Minas Gerais		Central West		Brazil	
Crops	Yield	Area	Yield	Area	Yield	Area
Soybean	2,930	1,151	2,970	12,901	2,928	27,907
Corn	6,130	1,215	5,750	6,238	5,254	15,280
Wheat	3,303	36.2	2,547	13	2,749	2,087
Rice	2,200	19.3	3,430	216	5,007	2,353
Sweet potato	15,770	1.97	31,530	0.32	13,091	38.6
White potato	31,444	40	38,734	5.3	27,752	128
Cassava	13,890	58.7	18,409	67.6	14,080	1,526

Table 2.5 Calculation factors to determine human digestible protein contents of food crops and pork

Product	Code [a]	DM*, [a] (kgDM/kg product)	Protein [a] (g/kgDM)	Protein digestibility [b] (%)
Soybean	16108	0.915	398.97	78
Corn	20014	0.896	105.10	87
Wheat	20074	0.904	125.07	87
Rice	20052	0.867	74.96	89
Sweet potato	11507	0.227	69.10	78[c]
White potato	11354	0.184	91.21	80[c]
Cassava	11134	0.403	33.70	91
Pork	10001	0.53 [d]	190 [e]	94

*DM: dry matter. [a] USDA (2014b). [b] Gilani *et al*. (2005). [c] Cited in Van Zanten *et al*. (2015a). [d] kg edible product per kg live weight (De Vries and De Boer, 2010). [e] g protein per kg edible product (De Vries and De Boer, 2010).

Table 2.6 Human digestible protein production (kg/ha) of food crops

Crops	Minas Gerais	Central West
Soybean	834.3	845.7
Corn	502.2	471.1
Wheat	324.9	250.8
Rice	127.3	198.4
Sweet potato	193.0	385.8
White potato	422.2	520.0
Cassava	171.7	227.5

2.2.4.4 Cumulative energy demand

Energy is a crucial input in feed production. It is used for crop cultivation, drying and processing, feed manufacturing and transport. Cumulative energy demand (CED) was used to assess both direct and indirect energy uses. Energy use positively affects GWP as the use of fossil energy is one of the main sources of GHGs emission. The CED required to produce feed for finishing a 104 kg LW pig was computed using the CED for each feed ingredient (Table 2.3), technical performance of pig production (Table 2.1) and diet compositions of sows, piglets and growing pigs (Appendix 2A, Table 2.A2), and finishing pigs (Table 2.2).

2.2.5 Feed cost

Cost of feed was calculated as the sum of the cost of feed ingredients in 2015 prices. For some ingredients (e.g. corn and SBM) annual market prices in 2015 in Brazilian Reals (R$) were used whereas for other ingredients (e.g. co-products, amino acids and mineral supplements) market prices in 2016 and for phytase price in 2009 were used (Appendix 2A, Table 2.A5). The market prices of feed ingredients were converted into US$ using the respective annual exchange rates and deflated using price indices with base year 2015. Price indices of feed were constructed as weighted average prices of corn and SBM (with weights of 75% for corn and 25% for SBM). This is because corn and SBM account for more than 80% in pigs' diets. The price indices used are 60% for 2009, 100% for 2015 and 125% for (January to May) 2016. The costs of feed are calculated using the composition of diets for sows, piglets and growing pigs (Appendix 2A, Table 2.A2), finishing pigs (Table 2.2) and the deflated prices of feed ingredients. The cost of feed for sows, piglets and growing pigs is presented in Appendix 2A (Table 2A.2). The cost of feed for finishing pigs is presented in the results section (Subsection 2.3.2).

As MKC is an emerging product, it is not traded in the market. We assumed that the by-product from macaúba oil extraction (i.e. macaúba cake) is a waste product with a price of zero at the oil processing factory level. Costs are incurred for drying and for transport from the macaúba processing plant to the feed mill. We assumed that drying of a ton of MKC requires 41 kWh of electricity and 20.5 kWh of natural gas. This is equivalent to the energy required to process an average ton of feed ingredient at a feed mill (Garcia-Launay *et al*., 2014). Using the 2015 prices of energy (i.e. R$0.25/kwh), calculated energy cost was US$0.005 per kg MKC. Assuming a 200 km distance between the macaúba processing plant and the feed mill, cost of truck transport was US$0.01 per kg MKC (www.ams.usda.gov/services/transportation-analysis/brazil-datasets). We assumed that other processing costs (e.g. labour cost) are negligible. Therefore, the processing cost of MKC (i.e. US$0.015/kg) was used as the price of MKC. In the sensitivity analysis, we increased the price of MKC based on the price of a similar product. The calculated cost of feed did not include cost of feed manufacturing (i.e. pelleting and grinding of feed ingredients) and transport cost of delivering feed from feed mill to pig farm. The exclusion of these costs does not affect comparison of costs among diets as these costs are assumed equal across all diets.

2.2.6 Sensitivity analysis

Sensitivity analysis was conducted to check the robustness of the results. We assumed that the production of MKC does not contribute to environmental impacts following the allocation of all impacts to the oil (i.e. zero economic allocation rate for the cake). However, commercialization of the production and processing system could make MKC a competitive product. We conducted a sensitivity analysis to see how the results change following the allocation of environmental impacts of macaúba production and processing to the different macaúba products. According to a preliminary assessment of production, processing and market situation of macaúba in Paraguay (Poetsch *et al*., 2012), MKC could generate about 5.4% of the total revenue from the sales of macaúba products (Figure 2.2). Although the absolute prices estimated by Poetsch *et al*. (2012) looks unrealistic (e.g. the price of MKC is US$0.18/kg, which is more expensive than corn), the relative prices can be used for deriving the economic allocation rates. Accordingly, in the sensitivity analysis, we assessed the environmental impacts of utilising MKC in the diets of pigs using an economic allocation rate of 5.4% for MKC and 94.6% for the rest of the macaúba products (Figure 2.2).

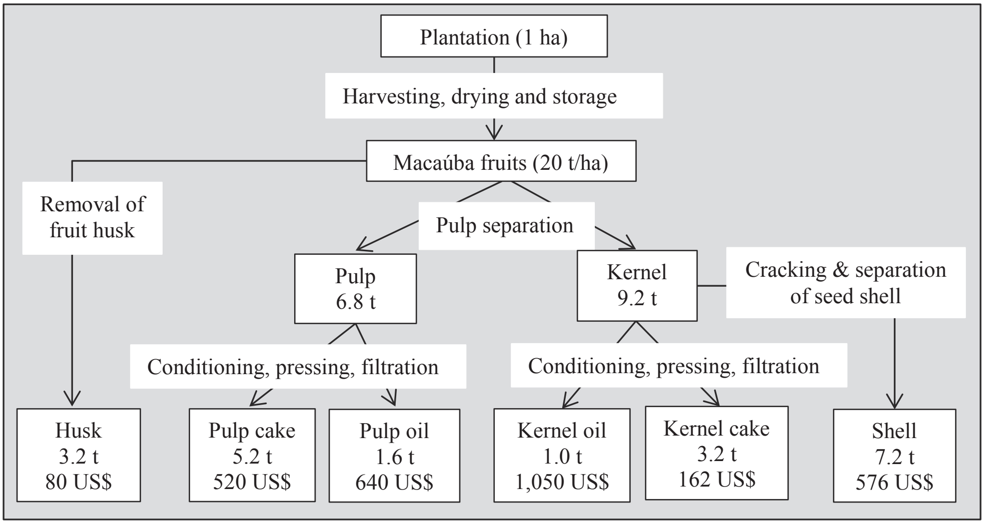


Figure 2.2 Processing, yield fractions and revenues of macaúba products (Poetsch *et al*., 2012)

Currently, there is no life cycle inventory data on input requirements for cultivation (e.g. fertiliser) and processing (e.g. energy) of macaúba. Due to lack of such data, we adopted the data from production and processing practices of Indonesian palm kernel as both palm kernel and macaúba are palm trees providing fruits for oil extraction. Following the (5.4%) allocation of environmental impacts of macaúba production and processing to MKC, the production and delivery of a kg of MKC to a feed mill in Minas Gerais resulted in a GWP of 0.66 kg CO_2-eq, LU of 0.59 m^2 and CED of 2.41 MJ. The respective original values were 0.02 kg CO_2-eq, 0.00 m^2 and 0.28 MJ.

We also assessed the impact of increasing the price of MKC equal to the price of palm kernel meal on economic results. This is equivalent to raising the price of MKC (US$/kg) from 0.015 to 0.12. The price estimated by Poetsch *et al*. (2012) (US$0.18/kg; Figure 2.2) for MKC was higher than the 2015 market price of corn in MG (about US$0.16/kg). Given the nutritional value of MKC relative to corn (net energy (MJ/kg) of 7.98 for MKC and 10.82 for corn), the price of MKC from Poetsch *et al*. (2012) (US$0.18/kg) is very expensive. Therefore, for the economic performance, we used the price of palm kernel meal in the sensitivity analysis.

2.3 Results

2.3.1 Environmental impacts

Global warming potential

Table 2.7 shows the GWP of the three scenarios with and without including LUC. When LUC is not included, GWP per kg LW is about 5.2% lower for MD-S and 1.1% lower for CD-S compared with RD-S whereas it is about 7% lower for MD-S and 3.4% lower for CD-S when dLUC is included. The use of co-products has reduced emission from LUC.

Table 2.7 Global warming potential (kg CO_2-eq per functional unit) of feed production and delivery at pig farm [a]

	Without LUC [b]			Including dLUC [c]			Including iLUC [d]		
Feed type	RD-S [e]	MD-S [e]	CD-S [e]	RD-S	MD-S	CD-S	RD-S	MD-S	CD-S
Finishing pigs	42.4	36.0	41.1	50.1	39.8	45.1	71.4	57.4	60.1
Growing pigs	48.2	48.2	48.2	58.0	58.0	58.0	80.8	80.8	80.8
Piglets & sows	33.1	33.1	33.1	38.8	38.8	38.8	52.16	52.16	52.16
Total	123.7	117.3	122.4	146.8	136.5	141.8	204.3	190.3	193.0
Per kg LW [f]	1.19	1.13	1.18	1.41	1.31	1.36	1.96	1.83	1.86

[a] Including production, drying, processing and transport of feed ingredients; and milling and transport of feed to pig farm. [b] Land use change. [c] Direct land use change. [d] Indirect land use change. [e] A corn-soybean meal-, macaúba kernel cake- and co-products-based finishing diets were used in the reference (RD-S), macaúba (MD-S) and co-products (CD-S) scenarios, respectively. Diets of sows, piglets and growing pigs, which were the same in the three scenarios, were considered. Net energy intakes were the same in the three scenarios. [f] Live weight.

Land use efficiency

Table 2.8 shows the land requirement to produce the feed required to finish a 104 kg LW pig for slaughter including feed for sow, piglets and growing pigs. Furthermore, it provides the HDP and LUR for the scenarios. About 0.56 m^2 land (10%) could be saved by using the alternative diets instead of RD to produce feed which is required to produce 1 kg live weight pig for slaughter.

The LUR results imply that the use of land for pig production is inefficient compared to using it for food crop production for direct human consumption. The LUR for RD-S (4.84; Table 2.8) implies that the land used (for feed production) to produce 1 kg HDP from pork could be used to produce 4.84 kg HDP from the production of food crops for direct human consumption. The entry 25.75 in Table 2.8 (first row, fourth column) indicates that the land used to produce corn in MG for feed which is required to produce one finished pig could be used to produce 25.75 kg HDP from direct production and consumption of food crops (i.e. soybean). The entries for MKC and citrus pulp are zeros since the land uses for these ingredients, which are suitable to produce food crops, are zero due to economic allocation. The alternative diet based scenarios (MD-S and CD-S) have lower LURs compared with the corn-SBM based diet scenario (RD-S). In terms of LU, CD-S and MD-S are better ways of producing pork relative to RD-S. The inclusion of co-products, use of synthetic amino acids and the production of feed ingredients on marginal land has reduced the LU inefficiency of pig production.

Table 2.8 Land use (LU), human digestible protein of food crops (HDP_j) that could grow on land used for feed production and land use ratio (LUR) per functional unit (FU)

	LU (m^2/FU)			HDP_j (kg/FU)		
Ingredients	RD-S [a]	MD-S [b]	CD-S [c]	RD-S [a]	MD-S [b]	CD-S [c]
Corn	308.68	300.22	271.17	25.75	25.05	22.62
Soybean meal	241.98	199.89	202.55	20.46	16.90	17.13
Wheat middlings	6.63	-	24.86	0.55	-	2.07
Sugarcane molasses	-	-	0.73	-	-	0.06
Soybean oil	3.05	3.05	3.05	0.26	0.26	0.26
Soybean hulls	4.78	4.78	4.78	0.40	0.40	0.40
Maize gluten meal	1.41	1.41	1.41	0.12	0.12	0.12
Rice bran meal	1.31	1.31	1.31	0.11	0.11	0.11
Macaúba kernel cake	-	0.00	0.00	-	0.00	0.00
Citrus pulp, dried	-	-	0.00	-	-	0.00
Total	567.84	510.66	509.87	47.66	42.84	42.78
HDP_{pig} (kg/FU)	-	-	-	9.84	9.84	9.84
LUR	-	-	-	4.84	4.35	4.35

[a] Reference diet scenario. [b] Macaúba kernel cake-based diet scenario. [c] Co-product-based diet scenario.

Cumulative energy demand

Table 2.9 shows the CED of the three scenarios. Relative to RD-S, CED per FU is 4.4% lower for MD-S and 7.0% higher for CD-S. Co-products require significant amounts of energy for processing and transportation (e.g. drying of citrus pulp and transportation of sugarcane molasses). Production of synthetic amino acids also requires a significant amount of energy.

Table 2.9 Cumulative energy demand (MJ/functional unit) of feed production and delivery at pig farm

Feed type	RD-S [a]	MD-S [a]	CD-S [a]
Finishing pigs	532.2	464.87	637.1
Growing pigs	575.6	575.63	575.6
Piglets and sows	404.4	404.37	404.4
Total	1,512.2	1,444.9	1,617.1
Per kg live weight	14.5	13.9	15.5

[a] A corn-soybean meal-, macaúba kernel cake- and co-products-based finishing diets were used in the reference (RD-S), macaúba (MD-S) and co-products (CD-S) scenarios, respectively. Diets of sows, piglets and growing pigs, which were the same in the three scenarios, were considered. Net energy intakes were the same in the three scenarios.

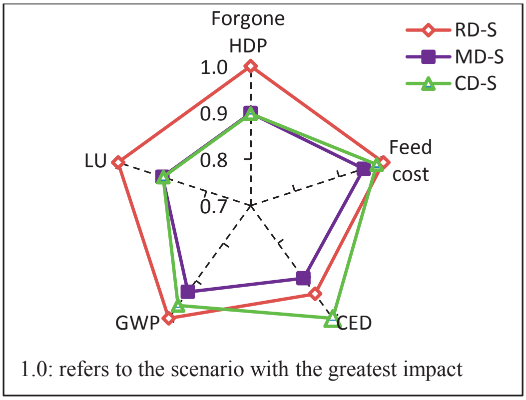
2.3.2 Feed cost and normalised impacts

The alternative finishing diets are cheaper than the reference diet with unit prices (US$/kg) of 0.221 for the reference diet, 0.189 for the macaúba kernel cake based diet and 0.210 for the co-product based diet. Compared with the price of the reference diet, prices are 14% lower for macaúba kernel cake based and 5% lower for co-product based diets. Compared with RD-S, costs of feed per FU are about 4.4% lower for MD-S and 1.5% lower for CD-S (Table 2.10).

Table 2.10 Cost of feed per kg of live weight (LW) and per functional unit (FU)

	Reference diet scenario	Macaúba kernel cake-based diet scenario	Co-product-based diet scenario
Cost (US$/kg LW)	0.65	0.62	0.64
Cost (US$/FU)	67.27	64.28	66.25

The normalised feed cost and environmental impacts are given in Figure 2.3. The MKC based scenario performed better than the reference scenario in all the five performance indicators. Compared with the CD-S, MD-S performed better in terms of GWP, CED and feed cost.



RD-S, reference diet scenario; MD-S, macaúba kernel cake based diet scenario; CD-S, co-product based diet scenario; LU, land use; Forgone HDP, forgone human digestible protein due to the use of cropland for feed production which would have been used for food crops production for direct human consumption; CED, cumulative energy demand; GWP, global warming potential.

Figure 2.3 Normalised feed cost and environmental impacts

2.3.3 Sensitivity analysis

The results of the sensitivity analysis are summarised in Table 2.11. Following the (5.4%) allocation of environmental impacts of macaúba production and processing to MKC, GWP (with and without including emission from LUC) increased by 3.6% to 10.3% for the alternative scenarios (MD-S and CD-S). Compared with RD-S, GWP is 4.6% and 3.8% higher for MD-S and CD-S, respectively. When dLUC is included, GWP is up to 1.2% higher for the alternative scenarios whereas it is up to 2.2% lower when iLUC is included. Land use and CED are also increased for the alternative scenarios following the allocation of impacts to MKC. Compared with RD-S, the new values of LU per FU are 8.1% and 9.2% lower for MD-S and CD-S, respectively; whereas CED per FU are 1.8% lower for MD-S and 8.3% higher for CD-S. The increase in the price of MKC (from US$0.015 to US$0.12) resulted in about 11.1% and 4.8% increase in the prices of MKC and co-product based finishing pig diets, respectively. Similarly, feed cost per FU increased by about 3.1% and 1.5% for MD-S and CD-S, respectively.

Table 2.11 Effects of raising the price of macaúba kernel cake (MKC) and allocating environmental impacts of macaúba production and processing to MKC

		RD-S [a]	MD-S [a]	CD-S [a]
Environmental impacts				
GWP (without LUC)	Zero economic allocation	123.7	117.3	122.4
(kg CO_2-eq/FU)	5.4% economic allocation	123.7	129.4	128.5
GWP with direct LUC (kg CO_2-	Zero economic allocation	146.8	136.5	141.8
eq/FU)	5.4% economic allocation	146.8	148.6	147.9
GWP with indirect LUC (kg	Zero economic allocation	204.3	190.3	193.0
CO_2-eq/FU)	5.4% economic allocation	204.3	204.1	199.9
Cumulative energy demand	Zero economic allocation	1512.2	1444.9	1617.1
(MJ/FU)	5.4% economic allocation	1512.2	1485.3	1637.3
Land use (m^2/FU)	Zero economic allocation	567.84	510.66	509.87
	5.4% economic allocation	567.84	521.95	515.51
Land use ratio (kg/kg)	Zero economic allocation	4.84	4.35	4.35
	5.4% economic allocation	4.84	4.45	4.40
Economic impacts				
Finishing pig feed price	Price of MKC (US$0.015/kg)	0.221	0.189	0.210
(US$/kg)	Price of MKC (US$0.12/kg)	0.221	0.210	0.220
Feed cost (US$/FU)	Price of MKC (US$0.015/kg)	67.27	64.28	66.25
	Price of MKC (US$0.12/kg)	67.27	66.26	67.23

GWP, global warming potential; LUC, land use change; FU, functional unit.
[a] A corn-soybean meal-, macaúba kernel cake- and co-products-based finishing diets were used in the reference (RD-S), macaúba (MD-S) and co-products (CD-S) scenarios, respectively. Diets of sows, piglets and growing pigs, which were the same in the three scenarios, were considered. Net energy intakes were the same in the three scenarios.

2.4 Discussion

This study assessed the three main global environmental issues of livestock production (i.e. climate change, land use and energy use). The comparison of the performance of the current system with the alternative systems has global implications as intensive pig production systems world-wide are mainly based on high quality grains (cereals and oilseeds) and as there is a growing availability of different kinds of co-products from the agro food and energy processing industries in different parts of the world. The use of co-products in the diets of pigs reduces the feed-food competition for cropland and thereby improves global food security. In the literature, studies that assessed the benefits of using co-products in reducing the feed-food competition are very limited (e.g. Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015b). In addition, as Brazil is one of the biggest producers and exporters of feed and meat in the world, a more efficient Brazilian production system will affect meat production elsewhere in the world due to the globalisation of feed and food production systems.

The MKC based diet scenario performs better than the other scenarios (in terms of both environmental and economic performance). This is partly the result of the assumption that the cake is a waste product with a price that is based only on processing and transportation costs. However, commercialization of the production and processing system may make MKC a competitive feed ingredient which will increase the price. As shown in the sensitivity analysis, a higher price of MKC increased the prices of the alternative finishing diets (MD and CD), and the environmental impacts (GWP, LU and CED) of the alternative scenarios (MD-S and CD-S) as environmental impacts are based on economic allocation. However, the land use change advantage of MKC (a component of GWP) remains, as does the land use advantage since macaúba can be grown on marginal lands and existing pastures. Nevertheless, like for any other co-product, a growing demand and a subsequent higher price for macaúba might also stimulate LUC on non-marginal lands.

Lack of significant economic incentives can jeopardize the utilisation of co-products by Brazilian pig producers as they have to compete in world markets. Costs of feed per finished pig are 1.5-4.4% lower for the alternative scenarios compared with the reference scenario. Such a small economic incentive might not be enough for producers to utilise co-products in place of the well-established corn-soybean meal based systems. However, concerned bodies (e.g. government) could stimulate the utilisation of co-products taking into account the environmental benefits and their potential to contribute to food security by making available cropland for food crops production.

The current study assessed the GWP, LU and CED of feed sources. However, in order to get a complete picture of the environmental impacts of using co-products in the diets of pigs and to avoid shifting of impacts from one category to another, other environmental effects (e.g. acidification and eutrophication) should also be addressed. However, according to a study by Mackenzie *et al*. (2016), the use of co-products in the diets of growing-finishing pigs did not affect acidification and eutrophication whereas it affected GWP and energy use. According to their results, compared with a standard corn-SBM based growing-finishing diet, maximum inclusion of corn distiller's dried grains with soluble (261 g/kg feed) in a growing-finishing diet increased GWP (16%) and non-renewable energy use (48%) per kg expected carcass weight whereas it decreased acidification potential (1%) and did not affect eutrophication potential. The same study showed that maximum inclusion of wheat shorts (291 g/kg) reduced both GWP (11%) and non-renewable energy use (18%) whereas it did not affect acidification and eutrophication potentials.

The comparison of the results from our study with the existing literature shows that our results for GWP and CED are lower (due to the lower environmental impacts of corn- explained below) than results in the literature whereas the results are comparable for LU (and LUR). A study by Mackenzie *et al*. (2016) showed that compared with a standard corn-SBM based growing-finishing diet, maximum inclusion of corn distiller's dried grains with soluble (261 g/kg feed) in a growing-finishing diet increased GWP (16%) and non-renewable energy use (48%) per kg expected carcass weight whereas maximum inclusion of wheat shorts (291 g/kg) reduced both GWP (11%) and non-renewable energy use (18%). These large differences between the effects of corn distillers and wheat shorts was due to the larger amount of energy requirement to produce corn distiller's dried grains (13.9 MJ/kg) than wheat shorts (1.2 MJ/kg). The result of the current study for the co-product based scenario are 1% lower for GWP and 7% higher for CED (where its main component is non-renewable energy use) compared with the reference scenario. Meul *et al*. (2012) showed that compared with a crop based reference diet, a ton of co-product based diet (with equal nutritional value) results in higher GWP when LUC is not included (13%) or when iLUC is included (2%), and a lower GWP when dLUC is included (1%). Besides LU is lower (22%). The results of the current study showed that compared with the standard corn-SBM based finishing diet, the co-product based finishing diet are lower for GWP when LUC is not included (3.2%), when dLUC is included (10.2%), when iLUC is included (16.2%) and lower for LU (10%). The reasons for the better performance of the co-product based diet in our study compared with the results of Mackenzie *et al*. (2016) and Meul *et al*. (2012) are the lower environmental impacts associated with MKC production and the lower emission factor used for corn in the current study.

Table 2.12 presents a comparison of the absolute level of the results in the present study with literature. The results of our study are expressed in four different units to be able to make the comparison with the other studies that use different units (Table 2.12). The difference between the result of our study for GWP (kg CO_2-eq) per kg live weight gain in the finishing phase (1.26 kg) and the result of Cherubini *et al*. (2014) (1.75 kg, Table 2.12) is due to the higher inclusion levels of products with high emission factors (e.g. soybean oil, SBM and synthetic amino acids) in the diets of Cherubini *et al*. (2014) and to the higher feed conversion ratio (kg feed/kg gain) that Cherubini *et al*. (2014) used (3.01) compared with the current study (2.82). The result of this study for GWP per kg LW is also lower compared with the results of Cherubini *et al*. (2015), Basset-Mens & van der Werf (2005), Van Zanten *et al*. (2015b) and Dourmad *et al*. (2014) (Table 2.12). This is due to two factors. First, we use a lower emission factor (0.367 kg CO_2-eq/kg) for corn compared with the emission factors used by these studies for energy source ingredients such as corn, wheat and barley. The emission factor for corn in our study is based on the current corn production system in the southern region of Brazil (Prudêncio da Silva *et al*., 2014; Alvarenga *et al*., 2012) which was estimated to be 6600 kg/ha. Other sources (e.g. Vellinga *et al*., 2013) use an emission factor of 0.711 kg CO_2-eq per kg corn based on an estimated corn production of 3600 kg/ha. In 2013, the average national corn productivity was 5254 kg/ha whereas it was greater than 6000 kg/ha for the southeast and southern regions (IBGE, 2015). The second factor is a higher slaughter weight and a longer period of feeding resulting in a higher feed conversion ratio (kg feed/kg body gain) in the literature compared to our study (e.g. 125 kg for Cherubini *et al*. (2015), 116 kg for Van Zanten *et al*. (2015b), 113 kg for Basset-Mens and van der Werf (2005) and 104 kg for this study). A higher slaughter weight and a longer feeding period lead to higher impacts as the daily weight gain generally decreases with increasing pig's age. The feed conversion ratios (from 24 kg to slaughter weight) were 2.48 for the current study, 2.51 for Cherubini *et al*. (2015), 2.44 for Van Zanten *et al*. (2015b) and 2.77 (from weaning to slaughter weight) for Basset-Mens and van der Werf (2005).

The difference between the results of our study and results of Van Zanten *et al*. (2015b) and Dourmad *et al*. (2014) for LU (Table 2.12) can also be explained by the difference in crop productivity and by the use of more co-products in the diets of pigs in Europe compared with the diets used in our study for Brazil. However, the result of the current study for LU (10.30 m^2/kg edible product) lies within the range of results as presented by De Vries and De Boer (2010) in their review paper (Table 2.12). The result of the current study for CED is also slightly lower compared with the results of the other studies (Table 2.12). This can also be due to a lower slaughter weight and shorter feeding period used in the current study compared with the other studies.

The LUR results of the current study (4.84 for RD-S, 4.35 for MD-S and CD-S) are comparable to the results of Van Zanten (2016). Van Zanten (2016) calculated LURs for the Dutch pig production system with a standard SBM-based finishing diet (4.6) and for scenarios where SBM was replaced by rapeseed meal (3.9-4.0) and waste-fed larvae meal (2.7) in the diets of finishing pigs. The slight difference between the results of our study and Van Zanten (2016) is due to the larger LU results in our study than Van Zanten (2016). The inclusion of co-products in the diets of finishing pigs reduces the competition for cropland between the feed and food sectors. Van Zanten *et al*. (2015a) also calculated land use ratios for Dutch laying hens and dairy cow production systems. Their results show a LUR of 2.08 for laying hens, 2.10 for dairy cows on sandy soils and 0.67 for dairy cows on peat soils. The LURs for pig production systems are higher than LURs for laying hens and dairy cows. This is due to the better feed conversion ratio for laying hens than pigs. The reason behind the lower LURs for the dairy production systems is the use of more co-products in the diets of cows and use of pasture unsuitable for growing food crops (e.g. peat soils).

Table 2.12 Global warming potential (GWP, kg CO_2-eq), Land use (LU, m^2) and Cumulative energy demand (CED, MJ) of feed production

Studies	Country	GWP	LU	CED
Per kg live weight gain (finishing phase)				
This study (Reference scenario)	Brazil	1.26 [a]		
Cherubini *et al*. (2014) (P18 scenario)	Brazil	1.75 [a]	-	-
Per kg live weight				
This study (Reference scenario)	Brazil	1.19[a]; 1.41[b]	5.46	14.54
Cherubini *et al*. (2015)	Brazil	2.31 [b]	-	17.81
Basset-Mens & van der Werf (2005) (GAP scenario)	France	1.68 [a]	5.43	11.77 [c]
Van Zanten *et al*. (2015b)	Netherlands	1.88 [a]	4.37	16.33 [c]
Dourmad *et al*. (2014) (conventional scenario)	Europe	1.53 [a]	4.13	11.52 [c]
Per kg carcass [d]				
This study (Reference scenario)	Brazil	1.51 [a]	6.93	18.45
Reckmann *et al*. (2013)	Germany	2.03	-	18.40 [c]
Per kg edible product				
This study (Reference scenario) [e]	Brazil	2.25 [a]	10.30	27.43
De Vries and De Boer (2010) [f]	OECD [g]	3.9-10	8.9-12.1	18-45 [c]

[a] Without accounting for land use change. [b] Accounting for direct land use change. [c] Non-renewable energy use which is the main component of CED. [d] Assuming 79% dressing percentage. [e] The edible amount was calculated based on De Vries and De Boer (2010). [f] Considering the whole cycle of pig production. [g] Organization for Economic Cooperation and Development.

2.5 Conclusions

The objective of the study was to assess the environmental and economic impacts of using co-products in the diets of pigs in Brazil. A corn-soybean based reference diet, a macaúba kernel cake based diet and a co-product based diet scenarios were designed. Inclusion of co-products in the diets of pigs has the potential to reduce environmental impact of pork production in terms of GWP and land use and to improve economic results. Compared with the reference diet scenario, GWP (including direct land use change) is 7.0% lower for macaúba kernel cake based scenario and 3.4% lower for co-product based diet scenario. Land use is 10% lower for the alternative scenarios. The results for the land use ratio (4.84 for the reference scenario and 4.35 for the alternative scenarios) imply that the production of pork using co-products could make available cropland for food crops production for direct human consumption. Compared with the reference diet scenario, cumulative energy demand per finished pig is lower for macaúba kernel cake (4.5%) and higher for co-product (7.0%) based scenarios. The inclusion of co-products in the diets of pigs is, therefore, an important strategy to reduce the impact on land use and emissions from land use change. Compared with the reference diet, the prices of the macaúba kernel cake based diet and the co-product based diet are 14% and 5% lower than the reference diet, respectively. The results of this study could be used by pig integrators to improve the environmental and economic sustainability of their current production system.

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Appendix 2A Supplementary material

Appendix 2.A1 Nutritional value of macaúba kernel cake

Due to lack of data from practice about the nutritional values and digestibility of macaúba kernel cake (MKC) for finishing pigs, we used digestibility coefficients of palm kernel meal (PKM). Both PKM and MKC are co-products of oil extraction from palm trees. As can be seen from Table 2.A1 below, the chemical compositions of PKM and MKC are comparable. The organic matter, crude protein and neutral detergent fibre contents are comparable. The main difference is the higher crude fibre content of MKC. Therefore, we assumed that the coefficient of the 'NSP fraction' is lower (60 %) for MKC compared to PKM (70%).

Table 2.A1 Composition and nutritional values of palm kernel meal (PKM) and macaúba kernel cake (MKC)

Main constituents (g/kg)	PKM [a]	MKC [b]	Digestibility coefficients for pigs (%) [a]
Dry matter	912	944.4	
Ash	43	50.5	
Organic matter	869	893.9	70
Crude protein	147	146.8	60
Crude fibre	196	391.4	48
Ether extract	83	113.2	76
Neutral detergent fibre	594	572.8	
Acid detergent fibre	358	426.7	
Acid detergent lignin	98	149.9	
Nitrogen free extract	443		81
Sugar and starch	20	40	100
Residue/NSP [c]	620	572.8	70 for PKM; 60 for MKC
Net energy (MJ/kg) [a]	7.64	7.98	

[a] CVB (2012). [b] Silva Junior (2015). [c] NSP (non-starch polysaccharides) calculated as organic matter – crude protein – ether extract – sugar – starch.

Based on Costa Junior *et al*. (2015), the mineral contents (g/kg) of MKC are: calcium 1.30 and phosphorus 0.8. The amino acid contents (% of CP) of MKC are: lysine 3.41, methionine 0.24, cystine 1.22, tryptophan 2.92, threonine 3.89, phenylalanine 3.16, tyrosine 2.68, leucine 6.08, isoleucine 3.41, valine 4.38, histidine 1.46 and arginine 4. 62. These amino acid concentrations of MKC are based on the pulp cake's composition corrected for the CP content (Costa Junior *et al*., 2015).

Table 2.A2 Diet composition for sows, piglets and growing pigs (adopted from Cherubini *et al*., 2015)

Ingredients (%)	Sows	Piglets [a]	Grower pigs [b]
Maize	60.23	55.02	66.67
Soybean meal	22.66	22.20	27.85
Soybean oil			0.33
Soybean hulls	6.42		
Maize gluten meal		3.00	
Dicalcium phosphate	0.99	0.45	0.35
Salt	0.49	0.26	0.52
Limestone	1.17	0.58	0.96
L-Lysine HCl	0.14	0.33	0.05
Dl-Methionine		0.03	0.02
Rice bran meal	5.24		1.26
Mineral and vitamin premix	0.30	7.17	0.27
Animal fat	2.12	3.43	0.45
Animal meal		3.28	1.26
Other amino acids	0.03	0.10	0.01
Other ingredients [c]	0.21	4.15	
Total	100.00	100.00	100.00
Total diet (kg/finished pig)	42	27.2	103 [d]
Cost of feed (US$/kg feed)	0.234	0.447	0.236

[a] Weaning to 23.7 kg live weight. [b] From 23.7 to 70 kg live weight. [c] Mycotoxin binders, flavours and sweetener agent (NB: not included in the environmental impact analyses). [d] Estimated based on Rostagno *et al*. (2011) and Cherubini *et al*. (2015).

Table 2.A3 Calculated nutrient contents of finishing pigs' diets

Nutritional values (g/kg)	Reference diet	Macaúba kernel cake-based diet	Co-product-based diet
Dry matter	873.94	890.26	881.27
Crude protein	177.13	143.74	145.87
AID LYS [a]	7.80	7.80	7.80
Crude fibre	27.86	97.07	73.34
Calcium	5.15	5.12	5.12
Phosphorus	4.56	3.86	4.52
Total lysine	9.31	9.28	9.23
Total methionine	2.88	3.19	3.16
Total met + cys	5.97	5.59	5.64
Total threonine	6.68	6.51	6.47
Total tryptophan	1.96	2.08	1.90
Net energy (MJ/kg)	9.83	9.83	9.83

[a] Apparent ileal digestible lysine.

Table 2.A4 Weighted average of feed usage and land use per finished pig [a]

Ingredients	Feed intake (kg/finished pig)			Land use (m^2/finished pig)		
	RD-S [b]	MD-S [c]	CD-S [d]	RD-S [b]	MD-S [c]	CD-S [d]
Corn	175.20	170.41	153.91	308.68	271.17	300.22
Soybean meal	67.39	55.67	56.41	241.98	202.55	199.89
Soybean oil	0.34	0.34	0.34	3.05	3.05	3.05
Soybean hulls	2.70	2.70	2.70	4.78	4.78	4.78
Macaúba kernel cake	0.00	19.00	9.50	0.00	0.00	0.00
Maize gluten meal	0.82	0.82	0.82	1.41	1.41	1.41
Rice bran meal	3.50	3.50	3.50	1.31	1.31	1.31
Wheat middlings	3.80	0.00	14.25	6.63	24.86	0.00
Citrus pulp, dried	0.00	0.00	4.75	0.00	0.00	0.00
Sugarcane molasses	0.00	0.00	3.80	0.00	0.73	0.00
Animal meal	2.19	2.19	2.19	0.00	0.00	0.00
Animal fat	2.29	2.82	5.75	0.00	0.00	0.00
Mineral and vitamin premix	2.73	2.73	2.73	0.00	0.00	0.00
Dicalcium phosphate	0.90	0.90	0.90	0.00	0.00	0.00
Monocalcium phosphate	0.30	0.49	0.36	0.00	0.00	0.00
Natrium bicarbonate	0.00	0.32	0.00	0.00	0.00	0.00
Limestone	2.28	2.24	2.04	0.00	0.00	0.00
Salt	1.20	0.97	1.17	0.00	0.00	0.00
L-lysine	0.25	0.58	0.54	0.00	0.00	0.00
DL-methionine	0.03	0.14	0.13	0.00	0.00	0.00
L-threonine	0.05	0.15	0.17	0.00	0.00	0.00
Phytase	0.01	0.01	0.01	0.00	0.00	0.00
Other ingredients	1.22	1.22	1.22	0.00	0.00	0.00

[a] Including feed for sows, piglets and growing pigs. [b] Reference diet scenario. [c] Macaúba kernel cake-based diet scenario. [d] Co-product-based diet scenario.

Table 2.A5 List of price of feed ingredients

Ingredients	Price (R$/kg)	Reference/remark
Corn	0.52	www.embrapa.br/en/suinos-e-aves/cias/precos; average price in MG in 2015 (assessed on 25 March 2016)
Soybean meal	1.23	www.embrapa.br/en/suinos-e-aves/cias/precos; average price in MG in 2015 (assessed on 25 March 2016)
Soybean oil	3.28	IEA, 2016; ciagri.iea.sp.gov.br/ ; average price in SP in 2015 (assessed on 25 March 2016)
Soybean hulls	0.62	Assuming its price is half of the price of SBM
Macaúba kernel cake	0.05	Cost of processing the cake-assuming it as a waste and only costs for processing.
Animal fat/tallow	2.80	February 2016 price in SP, biomercado.com.br/indicadoresPorProduto.php?produto=46
Animal meal	1.44	aliceweb.mdic.gov.br/ ; FOB price at Sao Paulo in 2015
Citrus pulp, pelleted	0.45	www.alcancepecuaria.com.br & UFV (2016 price)
Dicalcium phosphate	2.98	UFMG nutrition department (March 2016 prices)
Monocalcium phosphate	2.98	Assuming its price is the same with dicalcium phosphate
Sodium bicarbonate	2.8	UFMG nutrition department (March 2016 prices)
DL-methionine	32.36	UFMG nutrition department (March 2016 prices)
Limestone	0.26	UFMG nutrition department (March 2016 prices)
L-lysine	6.85	UFMG nutrition department (March 2016 prices)
L-threonine	12.44	UFMG nutrition department (March 2016 prices)
Maize gluten meal	1.49	www.conab.gov.br; 2015 price in MG (assessed on 25 March 2016)
Mineral & vitamin premix	10.90	UFV nutrition department (March 2016 prices)
Rice bran meal	0.6	IEA, 2016; ciagri.iea.sp.gov.br/ ; average price in SP in 2015
Salt	0.5	UFMG nutrition department (March 2016 prices)
Sugarcane molasses	1.92	Personal communication (March 2016 prices)
Wheat middling	0.233	www.agrolink.com.br; average price in Brazil in 2015 (assessed on 25 March 2016)
Phytase	34	Price in 2009 (Rodrigues, 2009)
Other ingredients [a]	3	Assumption (2015 price)

[a] Mycotoxin binders, flavours and sweetener agent.

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Chapter 3

A stochastic bio-economic pig farm model to assess the impact of innovations on farm performance

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Abstract

Recently developed innovations may improve the economic and environmental sustainability of pig production systems. Generic models are needed to assess the impact of innovations on farm performance. Here we developed a stochastic bio-economic farm model for a typical farrow-to-finish pig farm to assess the impact of innovations on private and social profits. The model accounts for emissions of greenhouse gases from feed production and manure by using the shadow price of CO_2, and for stochasticity of economic and biological parameters. The model was applied to assess the impact of using locally produced alternative feed sources (i.e. co-products) in the diets of finishing pigs on private and social profits of a typical Brazilian farrow-to-finish pig farm. Three cases were defined: a reference case (with a standard corn-soybean meal-based finishing diet), a macaúba case (with a macaúba kernel cake-based finishing diet) and a co-products case (with a co-products-based finishing diet). Pigs were assumed to be fed to equal net energy intakes in the three cases. Social profits are 34% to 38% lower than private profits in the three cases. Private and social profits are about 11% and 14% higher for the macaúba case than the reference case whereas they are 3% and 7% lower for the co-products case, respectively. Environmental costs are higher under the alternative cases than the reference case suggesting that other benefits (e.g. costs and land use) should be considered to utilise co-products. The coefficient of variation of farm profits is between 75% and 87% in the three cases following from the volatility of prices over time and variations in biological parameters between fattening pigs.

Keywords**:** Pigs, bio-economic model, environmental impact, stochasticity, profit

Implications

The developed model can be used to assess the impact of a wide range of innovations on private and social profits. It can also be used in breeding programs to derive economic values of breeding goal traits. Social profits are lower than private profits for a typical Brazilian farrow-to-finish pig farm suggesting that the society is incurring costs for the damages caused by emission of greenhouse gases which are not internalised by the producer. Environmental costs are higher for co-product-based diets than conventional diet suggesting that other benefits (e.g. costs and land use) should be considered to utilise co-products.

3.1 Introduction

Brazil is the fourth largest producer and exporter of pork in the world (United States Department of Agriculture, 2014). Pig production is based mainly on an intensive system using modern technologies. In recent years, the pig industry has faced rising feed costs (Embrapa Swine and Poultry Centre, 2016) and environmental problems such as emission of greenhouse gases (GHGs) following from feed production and manure (Cherubini *et al*., 2015; Ali *et al*., 2017). Innovations such as locally adapted production systems using alternative feed sources (Ali *et al*., 2017) and breeding programs better suited to local conditions (Kanis *et al*., 2005) might reduce these problems.

For making informed decisions about adopting innovations (e.g. alternative feed sources, feeding systems and breeding materials), farmers, breeders and other stakeholders need information on the impact of these innovations on farm performance. Bio-economic farm models (BEFMs) have proven to be useful tools for assessing the impacts of such innovations on technical, economic and environmental performances of farming systems (Janssen and Van Ittersum, 2007). A BEFM integrates biological, economic and management components of a system to explore diverse issues of farming. Several BEFMs were developed to assess the effects of— agricultural and environmental policies on farm performances of EU farming systems (Louhichi *et al*., 2010); management decisions on nutrient balance of dairy farms in the Netherlands (Buysse *et al*., 2005); agricultural policies on household income and soil fertility in Mali (Kruseman and Bade, 1998); and nitrate directives on farm income, nitrate leaching, soil erosion and water consumption of arable farms in France (Belhouchette *et al*., 2011). These models are, however, either location or purpose specific.

There are no generic BEFMs to assess the effects of different innovations on economic and environmental sustainability of intensive pig production systems. The application of BEFMs in pig farming has been limited to the assessment of the impact of improved breeding materials on farm (private) profit (e.g. Skorupski *et al*., 1995; Houška *et al*., 2004; Serenius *et al*., 2008). However, due to the growing demand for sustainable pork following from pull (e.g. growing consumer demand for environmentally friendly products) and push (e.g. environmental regulations) factors, farmers and their stakeholders need generic models that can be used to assess the effects of different innovations on both economic and environmental sustainability of pig production systems. The available BEFMs (e.g. Skorupski *et al*., 1995; Houška *et al*., 2004; Serenius *et al*., 2008) did not take into account the effects of innovations on social profit. In this study, social profit refers to private profit minus the environmental cost of pig production (and social cost refers to farm cost of production plus environmental costs that are not internalised by the farm). Next to that, most existing studies (e.g. Skorupski *et al*., 1995;

Houška *et al*., 2004) followed a deterministic approach for system parameters, even though some of these parameters are stochastic in nature. For example, prices of pork, feed and replacement gilts, which are the main economic parameters in pig production, fluctuate over time. There is also a biological variation between fattening pigs (e.g. daily growth and feed intake), which ultimately results in heterogeneous slaughter weights. Stochastic BEFMs take into account the variability of components in the system when exploring effects of changing technologies. A stochastic BEFM provides expected profit with its associated variance whereas a deterministic model calculates only profit based on the expected values of parameters. Since the model is nonlinear in biological parameters, a deterministic model provides wrong results. Price volatility and biological variation between pigs are sources of risk in pig farming. The decision making process of farmers depends on their risk preferences. Farmers are often risk averse (e.g. Gunjal and Legault, 1995). Price volatility and biological variations deter farmers from investing on innovations for increasing productivity and production, which in turn influences farm profit. Therefore, the incorporation of stochasticity in a BEFM enables to calculate the variability of farm profit which in turn provides insight into the utility of the producer that is derived from farming (e.g. via the mean-variance utility function).

In the light of the foregoing discussion, the objective of this study was to develop a stochastic BEFM as a tool for assessing the impact of innovations (e.g. alternative feeds, feeding systems and breeding materials) for a typical farrow-to-finish pig farm on private and social profits. The model was applied to the current Brazilian farrow-to-finish production system. The environmental aspect taken into account is GHGs emission. Risks associated with fluctuation of prices and variations in biological parameters are included in the model. The study is part of a project called 'Locally adapted pork production in Brazil' by Wageningen University & Research, Universidade Federal de Viçosa, TOPIGS Norsvin, and TOPIGS Norsvin do Brazil. The objective of the project is to improve the economic and environmental sustainability of pork production in Brazil by using locally produced alternative feed sources and by optimizing pig breeding.

3.2 Material and methods

3.2.1 Model design

Bio-economic farm models can take the form of a simulation model or an optimization model (Janssen and van Ittersum, 2007). This paper develops a simulation model rather than an optimization model, since the degrees of freedom for optimization are limited in an intensive pig production system. We assumed that available farm resources, which are given, (e.g. buildings and equipment) are optimally used and the farm operates at its optimum. The time period taken into account in the model is one year.

Figure 3.1 depicts the flow of inputs (feed and non-feed inputs) and outputs (both marketable and undesirable) and the production cycle of a sow and her piglets as it is modelled. Reproduction in the model starts with purchased replacement gilts from superior herd. Replacement gilts are mated (first mating) after a certain period of time from purchase. Conceived gilts join the sow pool. Gilts with problems (e.g. anoestrus, leg problems, udder problems, failed conception) are culled. The sow production cycle consists of conception, farrowing, lactation and weaning. After weaning, a sow will be mated or culled depending on her condition and performance. Weaned piglets pass through three growth stages— piglets (weaning to 23 kg), growing pigs (23-70 kg) and finishing pigs (70 kg to slaughter weight).

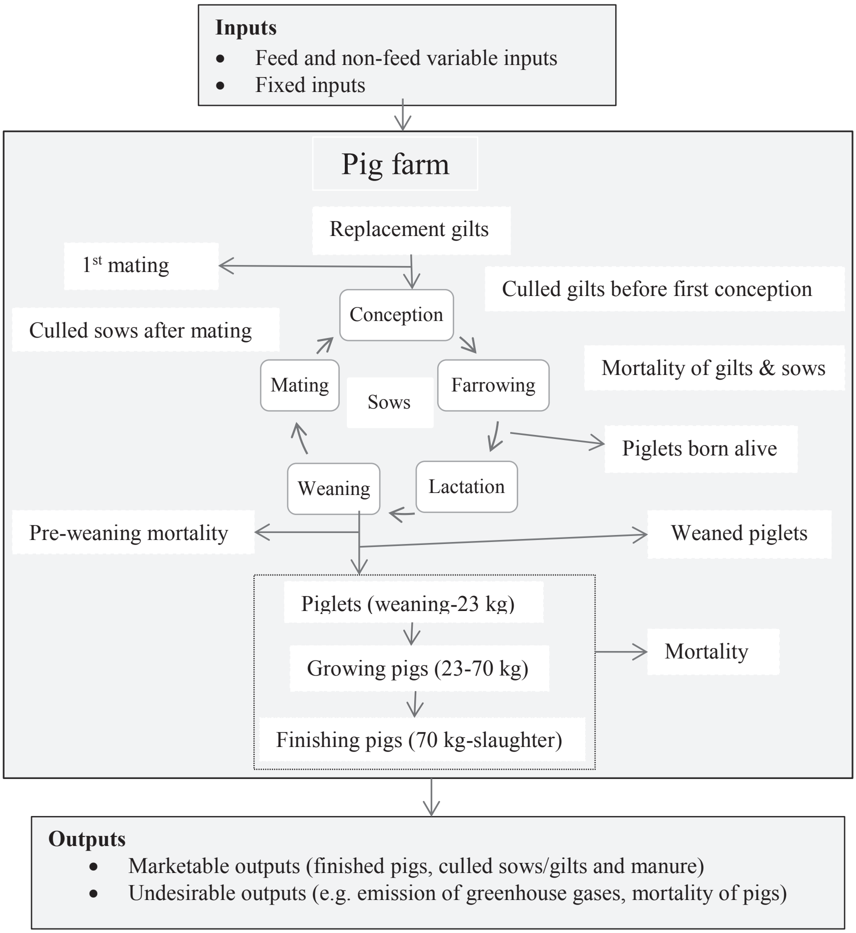

Figure 3.1 Flow chart of farrow-to-finish pig production system

Variable costs of gilts and sows comprise costs of purchasing replacement gilts, feed, labour, veterinary, energy, semen, maintenance and repair, transport and others. Boar costs are included in gilt and sow costs. Variable costs of fattening pigs include costs of feed, labour, veterinary, energy, maintenance and repair, transport and others during the three growth stages. Fixed costs (depreciation and interest expenses) are included at farm level. In the social profit function, environmental costs of emission of GHGs from feed production and manure, and the fertilizer value of manure are also included. Returns consist of sales of culled gilts and sows, of fattening pigs, and of the fertilizer equivalent value of manure. Appendix 3.A1 provides the list of equations used to calculate the costs and returns of sows and fattening pigs.

3.2.2 Pig growth model

A pig growth model, InraPorc® model, is incorporated in the BEFM to account for the biological aspects of growing-finishing pigs (23 kg to slaughter weight) using different diets. The model predicts growth performance of pigs (i.e. daily gain, feed conversion ratio, pork quality) for different types of diets used in the growing and finishing growth stages (Van Milgen *et al*., 2008). Protein deposition (PD) and lipid deposition (LD) are the two key variables related to chemical and physical body composition of pigs for predicting growth response and carcass characteristics. The InraPorc® model simulates nutrient partitioning for PD, LD and for other activities such as maintenance, physical activities and PD cost. The rate of PD and LD depends on potential PD, energy and amino acid supplies. Potential PD refers to PD when the pig is capable of expressing its full growth potential under *ad libitum* feeding. To predict feed intake in the InraPorc® model, the equation $Y = aX^b$ was used; where Y is net energy intake in MJ/day, X is body weight in kg, and a and b are parameters. The parameters a and b are estimated within InraPorc® from given feed intakes at 50 kg and 100 kg body weights. Other parameters required for simulating growth performance in InraPorc® are: initial age, initial body weight, final age or final weight, precocity per day and mean PD per day.

3.2.3 Environmental cost of feed and manure

Feed production and manure are the largest contributors to global warming potential (GWP) in the pork production chain (Nguyen *et al*., 2012; Cherubini *et al*., 2015). The environmental cost of GWP, which is caused by emission of GHGs, from feed production and manure, is incorporated in the BEFM. Global warming potential is selected as it generally also acts as an indicator of other environmental categories (e.g. acidification and eutrophication) (Röös *et al*., 2013). An efficient use of nitrogen leads to less acidifying and eutrophying substances being released to the environment and lower GHGs emission in the form of N_2O.

Two steps are required to calculate the environmental costs of feed and manure: determining the amounts of GWP from feed production and manure, and monetizing GWP. The GWP of feed productions were taken from Ali *et al*. (2017). The GWP of feed production included emissions from extraction of raw materials (e.g. fertilizer, pesticide and energy), cultivation of crop ingredients (including emissions from direct land use change), drying and processing of ingredients, manufacturing of concentrated feed and transportation in all stages until the pig farm. The GWP from manure depends on manure management and the type of diets used (Dourmad *et al*., 2003; Rigolot *et al*., 2010). The calculation of this GWP for the different diets is presented below in Subsection 3.2.5.4. The three GHGs: CO_2, CH_4 and N_2O were expressed in kg of CO_2 equivalent (CO_2-eq) using weights of 1, 28 and 265 for CO_2, CH_4 and N_2O, respectively (assuming 100 years life span; IPCC, 2015).

Monetizing GWP was done by using the shadow price of CO_2 emission. Several studies estimated the cost of CO_2 release to the atmosphere (for an overview see Tol, 2008). These costs are associated with the impact of CO_2 release on the environment, human health and economy. There is a huge variation among the estimates in the literature (see Tol, 2008). Although a shadow price represents the costs of damages on environment, resources and human health caused by CO_2 release, it is also a politically negotiated price for carbon. In this study, we used estimates from Gurgel and Paltsev (2014) for Brazil. During the 2009 Copenhagen meeting, Brazil agreed to reduce GHG emissions by between 36.1% and 38.9% by 2020. Gurgel and Paltsev (2014) examined a sectoral carbon tax, carbon tax on land use change, and establishing a carbon market for emission allowance trading from the agricultural and energy sectors together with a carbon tax on land use change to achieve this target. In this study, we used the average of the 2015 carbon tax for the livestock sector (about 0.07 US$/kg CO_2-eq) and carbon market price (about 0.02 US$/kg CO_2-eq). Even though two prices cannot exist together from economic point of view, we used the average of carbon tax and carbon market price since the carbon market price that Gurgel and Paltsev (2014) estimated does not account for emissions from land use change caused by the livestock sector. The shadow price that we used in this study (0.045 US$/kg CO_2-eq) is comparable with the shadow price estimated by Price *et al*. (2007) for UK (0.048 US$/kg CO_2-eq for 2015). For manure, we considered the financial gains due to the replaced fertiliser and reduction in GHGs emissions after taking account of GHG emissions from manure (refer to Subsection 3.2.5.4 for the Brazilian situation).

3.2.4 Stochastic variables

The BEFM accounts for the stochasticity of the main economic parameters (i.e. feed prices, the price of replacement gilt and the selling price of finished pig). The reason for choosing these stochastic parameters is that these variables fluctuate over time and they are expected to have substantial influence on the economic results as feed cost accounts >75% in pig cost of production and as sales of finished pigs are the main source of revenue. Fluctuations in feed prices follow the fluctuation of corn and soybean meal prices, which are the main feed ingredients.

The stochasticity of biological parameters (i.e. InraPorc® model parameters— mean PD, precocity per day, and net energy intakes at 50 kg and 100 kg live weights) was also considered. Performance variation among growing-finishing pigs is one of the main problems encountered by pig producers, which ultimately results in heterogeneous slaughter weights. For example, feed intake, nutrient utilisation and daily growth vary between growing-finishing pigs, which in turn result in different nutrient excretions. The inclusion of stochasticity in the InraPorc® model parameters captures the variations in performance among growing-finishing pigs (e.g. daily growth, feed intake, feed conversion and excretion of nutrients). Since the model is for a typical farm, we believe that there will be no random variations in management practices over time. Only variations external to the farm (e.g. prices and biological variations between pigs) are considered. We assumed that the performance of sows in the same age structure is the same and hence random variation between the performances of sows is negligible. Introduction of stochasticity in models requires average values, the variation of the stochastic variables, and the correlation among these variables. For prices, standard deviations and correlation coefficients can be derived from annual data by removing the effect of the trend term. For the InraPorc® model parameters, standard deviations and correlation coefficients can be computed from data recorded on a given farm.

3.2.5 Model application

The developed stochastic BEFM is applied to an independent (i.e. farrow-to-finish) pig farm in Minas Gerais to assess the impact of using alternative feed sources on private and social profits. Pig producers in Minas Gerais (and the southeast region) generally follow a farrow-to-finish production system. In Brazil, such producers are named ‘independent producers’ as these producers do not have contractual agreements with agribusinesses for receiving inputs (e.g. feed and piglets) or supplying their finished pigs. In Minas Gerais, the size of farms varies significantly ranging from 50 sows to more than 5,000 sows. We assume that a typical farm in our model owns 1,500 productive sows with annual replacement rate of 45% (Martins *et al.*, 2012). Embrapa Swine and Poultry Centre (2016) also assumes 1,500 productive sows in their monthly reports of swine cost of production for Minas Gerais.

3.2.5.1 Definition of cases

A reference case and two alternative cases (macaúba and co-products) are designed to assess the impact of using co-products in the diets of finishing pigs on private and social profits. The reference case represents the current feeding practice in Minas Gerais, Brazil. Table 3.1 shows the complete diet compositions used in the three cases.

Table 3.1 Diet compositions for pigs in Minas Gerais, Brazil (% of diet in kg product)

	The same for all cases			Reference case[1]	Macaúba case[1]	Co-prod. case[1]
	Sows[2]	Piglets[2]	Growing pigs[3]	Finishing pigs[3]		
Maize	60.23	55.02	72.25	80.15	64.71	47.35
Soybean meal	22.66	22.20	23.30	16.70	12.03	12.81
Macaúba kernel cake					20.00	10.00
Soybean oil			1.40	0.60		
Wheat middlings						15.00
Citrus pulp, dried						5.00
Sugarcane molasses						4.00
Animal fat	2.12	3.43			0.56	3.65
Animal meal		3.28				
Rice bran meal	5.24					
Soybean hulls	6.42					
Maize gluten meal		3.00				
Dicalcium phosphate	0.99	0.45	1.20	0.90		
Monocalcium phosphate					0.52	0.38
Sodium bicarbonate					0.34	
Salt	0.49	0.26	0.46	0.46	0.17	0.38
Limestone	1.17	0.58	0.59	0.53	0.63	0.42
L-Lysine	0.14	0.33	0.33	0.27	0.40	0.36
Dl-Methionine		0.03	0.10	0.03	0.12	0.11
Threonine 98%	0.03	0.10	0.08	0.07	0.11	0.13
Mineral & vitamin premix	0.30	7.17	0.30	0.30	0.40	0.40
Phytase[4]					0.01	0.01
Other ingredients[5]	0.21	4.15				
Total (%)	100	100	100	100	100	100
Nutritional values						
Net energy (MJ/kg)	-	-	10.25	10.26	9.83	9.83
Std. dig lysine (g/kg)[6]	-	-	9.99	8.00	8.14	8.14

[1] A corn-soybean meal-, macaúba kernel cake- and co-products-based finishing diets were used in the reference, macaúba and co-products cases, respectively. Diets of sows, piglets and growing pigs, which were the same in the three cases, were considered. Net energy intakes were the same. [2] Cherubini *et al*. (2015). [3] The growing and reference finishing pig diets were formulated based on data from a feed company by Gabriel Rocha, Department of Animal Sciences, Universidade Federal de Viçosa , Brazil. The alternative finishing diets were taken from Ali *et al*. (2017). [4] Equivalent to 500 FTU phytase per kg diet. [5] Mycotoxin binders, flavours and sweetener agent (not included in the environmental impact analyses). [6] Standardised ileal digestible lysine.

A three stage-feeding regime is assumed for fattening pigs based on piglets (weaning to 23 kg live weight), growing pigs (23 kg to 70 kg) and finishing pigs (70 kg to slaughter weight). Although it is possible to predict growth performance from 15 kg to slaughter using the InraPorc® model, we assumed that the piglet stage (weaning to 23 kg) is exogenous to the model to match with the Brazilian production system. The three cases have a common part (i.e. the diets for sows, piglets and growing pigs) and a specific part (i.e. diets for finishing pigs). The cases are specific for only the finishing stage because the digestibility of co-products (which are used in the alternative finishing diets) is lower compared to corn and soybean meal while the digestive capacity of finishing pigs is better than that of piglets and growing pigs. Moreover, a significant amount of feed is used in the finishing stage. The growing pig and the reference finishing pig diets were formulated to represent the current feeding practices in Minas Gerais. The finishing pig diet in the reference case mainly consists of corn and soybean meal. In the macaúba and co-products cases, a macaúba kernel cake- and a co-products-based diets are used during the finishing stages, respectively. The alternative finishing pig diets were taken from Ali *et al*. (2017). Total net energy intakes are set to be equal in the three cases.

3.2.5.2 Management, biological and economic input parameters

A farm that owns 1,500 productive sows with an annual replacement rate of 45% is assumed. The average (2006-2015) litter size born alive and pre-weaning mortality rates are about 12 piglets and 8.74%, respectively. Table 3.2 presents the values of management and biological input parameters of the model. Total net energy intakes are set to be equal in the three cases through the parameters net energy intakes at 50 kg and 100 kg body weights. We assumed that net energy intakes of growing-finishing pigs are 21.07 and 28.94 MJ/day at 50 and 100 kg body weights, respectively (Monteiro *et al*., 2016). Since the alternative diets of finishing pigs (macaúba kernel cake and co-products based diets) contain lower net energy concentrations (9.83 MJ/kg, Table 3.1) compared with the reference diet (10.26 MJ/kg, Table 3.1), pigs are allowed for a higher feed intake under alternative cases to realise the same net energy intake as the reference case. However, the higher feed intakes also result in increased feed costs and GHGs emissions.

The economic input parameters of the model are presented in Table 3.3. The expected prices of replacement gilts and of finished pigs are the averages of annual prices in the period 2006-2015. Annual prices of feeds for piglets, growing pigs, finishing pigs and sows were only available for the year 2015 from Ali *et al.* (2017) who computed them using information on the composition and the prices of feed ingredients. Other information available were the annual feed costs of finished pigs from a database of Embrapa Swine and Poultry Centre for the entire period 2006-2015. The missing feed prices in the period 2006-2014 were computed in two steps. First, we computed the annual percentage change in the feed costs of finished pigs for the period 2006-2015. Next, we used the annual changes in feed cost to compute feed prices for the period 2006-2014 from the 2015 prices of feeds. By doing this, we assumed that the annual changes in feed cost per finished pig over the period 2006-2015 are entirely due to changes in feed prices between the same years.

Table 3.2 Management and biological inputs of pig production in Minas Gerais, Brazil

Parameters	Values	Reference
Number of sows per farm	1,500.00	Embrapa Swine and Poultry Centre
Annual replacement rate of sows (decimal)	0.45	Martins *et al*. (2012); Dias (2016)
Age of gilts at purchase (days)	150.00	Dias (2016)
Age of replacement gilt at first oestrus (days)	180.00	Dias (2016)
Number of oestrus at first mating	3.00	Martins *et al*. (2012); Dias (2016)
Extra days open due to reproduction problems (days)	1.20	Dias (2016)
Farrowing rate (decimal)	0.88	Agriness (2016)
Service repetition rate (decimal)	0.07	Agriness (2016)
Gestation length (days)	114.00	Martins *et al*. (2012); Dias (2016)
Lactation length (days)	28.00	Martins *et al*. (2012)
Interval between weaning and oestrus (days)	7.00	Assumption (range: 4-10)
Feed usage of gilts, gestating and dry sows (kg/day)	2.80	Dias (2016)
Feed usage of sows during lactation (kg/day)	6.81	Dias (2016)
Mortality rate of replacement gilts till conception (decimal)	0.01	Dias (2016)
Mortality rate of sows (decimal)	0.05	Dias (2016)
Culling rate of replacement gilts till conception (decimal)	0.08	Dias (2016)
Culling rate of sows (decimal)	0.36	Own calculation[1]
Weaning-culling interval (days)	35.00	Dias (2016)
First insemination-culling interval (days)	17.50	Dias (2016)
Live weight of culled gilts (kg/gilt)	135.40	Dias (2016)
Live weight of culled sows (kg/sow)	225.00	Dias (2016)
Piglets born alive per sow per farrowing	12.02	Agriness (2016)
Weight of piglet at birth (kg/piglet)	1.34	Dias (2016)
Pre-weaning piglet mortality rate (decimal)	0.09	Agriness (2016)
Piglet weaning weight (kg/piglet)	7.50	Martins *et al*. (2012)
Feed usage of piglet (kg/piglet)	25.00	Martins *et al*. (2012)
Body weight of piglet (at 63 days age) (kg/piglet)	23.00	Martins *et al*. (2012)
Mortality rate of piglets and growing pigs (decimal)	0.02	Own calculation[2]
Mortality rate of finishing pigs (decimal)	0.03	Dias (2016)
Net energy intake at 50 kg body weight[3] (MJ/kg)	21.07	Monteiro *et al*. (2016)
Net energy intake at 100 kg body weight[3] (MJ/kg)	28.94	Monteiro *et al*. (2016)
Precocity per day[3] (decimal)	0.0105	Monteiro *et al*. (2016)
Mean protein deposition[3] (g/day)	131.00	Monteiro *et al*. (2016)
Duration in growing-finishing stage (days)	105.00	Rocha (2016)

[1] Derived from annual sow replacement rate, replacement gilt culling and death rates, and sow death rate. [2] Derived from weaned piglets per sow per year, number of finished pigs per sow per year and mortality rates in the finishing stage. [3] For gilts with standard performance.

Table 3.3 Economic input values of pig production in Minas Gerais, Brazil

Parameters	Values	Remark/reference
Piglet production		
Price of replacement gilts (R$/gilt)	516.24	www.agricultura.pr.gov.br
Semen cost (R$/pregnancy/sow)	23.14	Appendix 3A, Table 3.A1
Sow non-feed-semen variable cost (R$/day)	2.17	Appendix 3A, Table 3.A1
Replacement gilt non-feed variable cost (R$/day)	1.80	Assuming 83% of daily sow variable cost (Serenius *et al*., 2008)
Sow feed price (R$/kg)	0.61	Own computation[1]
Piglet feed price (R$/kg)	1.23	Own computation[1]
Price of culled sow (R$/kg live weight)	2.83	Average price (2006-2015)[2]
Price of culled gilt (R$/kg live weight)	1.82	Average price (2006-2015)[2]
Growing-finishing		
Cost of labour (R$/finished pig)	3.37	Appendix 3A, Table 3.A1
Cost of veterinary (R$/finished pig)	2.14	Appendix 3A, Table 3.A1
Cost of energy (R$/finished pig)	1.22	Appendix 3A, Table 3.A1
Other variable costs (R$/finished pig)	13.69	Appendix 3A, Table 3.A1
Growing pig feed price (R$/kg)	0.64	Own computation[1]
Finishing pig feed price (R$/kg)		
Reference diet	0.57	Own computation[1]
Macaúba kernel cake based diet	0.50	Own computation[1]
Co-product base**d** diet	0.56	Own computation[1]
Price of finished pig (R$/kg live weight)	3.02	www.agrocotacoes.com.br
Fixed cost per farm (R$/year)	1,016,073	Appendix 3A, Table 3.A1

R$ = Brazilian Real.

[1] Average feed prices (2006-2015) derived from annual feed cost of finished pig (Embrapa Swine and Poultry Centre, 2016). [2] Derived based on the relative price of live weight of culled gilts (R$3.45/kg) and sows (R$2.22/kg) compared to the average price of live weight of finished pigs (R$3.45/kg) from January to July 2016 in Passos, MG.

3.2.5.3 Stochastic input parameters

Feed prices, the price of replacement gilts and the selling price of finished pigs were assumed to be stochastic in the BEFM. Annual data (2006-2015) were used to compute the means, standard deviations and correlations among these stochastic parameters. Prices were de-trended (i.e. the systematic increase or decrease in prices was removed from the original prices) to generate a price series that was used for computing the standard deviations and correlations.

For the InraPorc® model parameters, the mean values were taken from Monteiro *et al*. (2016) which were estimated from the Brazilian production system. For the standard deviations and correlation coefficients among these parameters, values were adopted from Saintilan *et al*. (2015) who derived them based on experimental data from France. Since the Brazilian production system is also based on high potential breeds using modern technologies, we assume that the values reflect the variation in Brazil. Therefore, the variance captures performance differences between individual pigs. A normal distribution was assumed for both economic and biological parameters. Table 3.4 summarizes the mean values, standard deviations and correlation coefficients of the stochastic parameters. Since prices and biological parameters cannot be negative, the distributions of the parameters were truncated at zero (i.e. the minimum value is zero). Simulations were conducted using @Risk, an add-in in MS Excel (Palisade Corporation, Ithaca, NY).

3.2.5.4 Environmental cost of feed and net return from manure

The GWP (including emissions from direct land use change) of feed ingredients were taken from Ali *et al*. (2017). Using the emission factors of feed ingredients and diet compositions, GWP of each diet was derived. Manure is the second source of GHGs emission in pig production. For storage of manure, an open slurry tank (without a natural crust cover) is assumed, as this is the most commonly used form of pig manure management system in Brazil. The liquid manure is assumed to be removed daily or weekly from the channels of the building through pipes to the external deposit (slurry tank) where it is kept for about 120 days for partial stabilization and subsequent field application (Kunz *et al*., 2009; Cherubini *et al*., 2014). For estimating CH_4 and (indirect) N_2O emissions from manure, the tier 2 approach of IPCC was used by using country and diet specific data and IPCC (2006) default values. The country specific data concern the volatile solids and nutrient excretions of sows and piglets. For sows and piglets, these data were taken from Cherubini *et al*. (2014) and Diesel *et al*. (2002). For pigs in the growing and finishing stages, the mathematical models of Rigolot *et al*. (2010) and Dourmad *et al*. (2003) were included in the BEFM to calculate the amounts of volatile solids and nutrient excretions for the specific diets used. There is no direct N_2O emission since manure is stored in an open slurry tank without natural crust cover (IPCC, 2006; Cherubini *et al*., 2014). Appendix 3A (Appendix 3.A2 and Table 3.A2) provide the details of calculations for estimating volatile solids, nutrient excretions and GWP of manure.

In Brazil, manure is applied on land as organic fertilizer and thereby avoids the production and use of artificial fertilizer (Kunz *et al*., 2009; Cherubini *et al*., 2015). To calculate the returns from manure we assume that the avoided fertilizers are urea (46% N), superphosphate (42% P_2O_5) and potassium chloride (60% K_2O). Efficiency rates of 0.75 for urea (Nguyen *et al*., 2010), 1 for superphosphate and 1 for potassium chloride were assumed to estimate the amounts of avoided fertilisers. The amounts of avoided chemical fertilisers are then calculated as:

$$F_N = \frac{0.75 \times N_{Manure}}{0.46} \quad (3.1)$$

$$F_{P2O5} = \frac{1 \times P2O5_{Manure}}{0.42} \quad (3.2)$$

Table 3.4 Mean values, standard deviation and correlation coefficients among stochastic parameters

Parameters	Mean	SD	Correlations											
			A	B	C	D	E	F	G	H	I	J	K	L
Price of finished pig (R$/kg; A)	3.02	0.290	1.00	0.79	0.21	0.21	0.21	0.21	0.21	0.21	0.00	0.00	0.00	0.00
Price of replacement gilt (R$/gilt; B)	516.24	27.070		1.00	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
Piglet feed price (R$/kg; C)	1.23	0.098			1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Growing pig feed price (R$/kg; D)	0.64	0.051				1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Sow feed price (R$/kg; E)	0.61	0.049					1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Finishing pig feed price (R$/kg)														
Reference diet (F)	0.57	0.045						1.00	1.00	1.00	0.00	0.00	0.00	0.00
Macaúba-based diet (G)	0.50	0.040							1.00	1.00	0.00	0.00	0.00	0.00
Co-products-based diet (H)	0.56	0.045								1.00	0.00	0.00	0.00	0.00
Protein deposition (g/day; I)	131.00	11.000									1.00	0.07	0.33	0.09
Net energy intake at 50 kg body weight (MJ/kg; J)	21.07	2.000										1.00	0.19	0.11
Net energy intake at 100 kg body weight (MJ/kg; K)	28.94	3.000											1.00	-0.03
Precocity per day (decimal; L)	0.01	0.004												1.00

$$F_{K2O} = \frac{1 \times K2O_{Manure}}{0.60} \quad (3.3)$$

where F_N is the amount of urea, N_{Manure} is the total N excretion in the manure adjusted for N volatilisation during storage, F_{P2O5} is the amount of superphosphate, $P2O5_{Manure}$ is the amount of P_2O_5 in the manure, F_{K2O} is the amount of potassium chloride and $K2O_{Manure}$ is the amount of K_2O in the manure. Then, the net return from manure is computed as:

$$Net\ return\ from\ manure = \sum P_i \times F_i + \sum SP \times GWP_{F_i} - SP \times GWP_{Manure} \quad (3.4)$$

where P_i is price of artificial fertilizer $i;$ i refers to N, P_2O_5 and K_2O; F_i is amount of avoided fertilizer i; SP is the shadow price of GWP; GWP_{F_i} is GWP of artificial fertilizer production and GWP_{Manure} is GWP of manure. The first term ($\sum P_i \times F_i$) refers to the fertilizer value of manure, the second term ($\sum SP \times GWP_{F_i}$) implies the avoided environmental cost due to the avoided production of artificial fertilizer and the last term ($SP \times GWP_{Manure}$) is the environmental cost of manure. Appendix 3A (Table 3.A3) provides the details of calculations and parameter values for computing the net return from manure.

3.2.6 Sensitivity analysis

We checked the sensitivity of private profit due to a change in the price of the macaúba kernel cake based diet. As discussed in Ali *et al*. (2017), the price of macaúba kernel cake was based on only processing cost as the product is non-existent in market. Commercialization of the production and processing system of macaúba, however, might make it a competitive product. Therefore, in the sensitivity analysis we assumed an increase of the price of the macaúba kernel cake based finishing diet by 14%. This increase would make the price of the macaúba kernel cake based diet equal to the price of the reference diet.

3.3 Results

Table 3.5 presents the simulated pig growth performance results and nutrient excretions of the growing-finishing stage for the three cases. Carcass characteristics (i.e. slaughter weight, protein and lipid masses) are equal among the three cases. Average daily gain is also equal in the three cases as daily net energy intake was set equal in the three cases. The reference case resulted in better feed conversion ratio than the alternative cases since the net energy concentration of the reference finishing pig diet (10.26 MJ/kg) is larger than of the alternative finishing pig diets (9.83 MJ/kg). Since pigs were allowed the same net energy intake under the three cases, total feed intakes are larger under the alternative cases (252 kg) compared with the reference case (246 kg). Feed intake is equal for macaúba and co-products cases since the nutritional values of the diets used in these two cases were equal. The excretions of volatile solids are greater under the macaúba (27 kg/pig) and co-products (26 kg/pig) cases than the reference case (18 kg/pig). This is due to the higher fibre concentrations in the alternative diets of finishing pigs (97.1 g/kg for macaúba kernel cake based diet and 73.3 g/kg for co-products based diet) than the reference diet (23.3 g/kg). Nitrogen excretion is slightly higher under the alternative cases (by about 140 g per finished pig) following from the higher feed intakes although the crude protein concentrations of the diets are comparable (144.2 g/kg for the reference diet, 143.7 g/kg for macaúba kernel cake based diet and 145.9 g/kg for co-products based diet). Table 3.5 also shows the performance variations among growing-finishing pigs (e.g. live weight at slaughter, feed conversion ratio and nutrient excretions) following from the variations in mean PD, precocity per day and net energy intakes at 50 kg and 100 kg live weights. For example, the coefficient of variation of live weights of finished pigs at slaughter is about 12% implying the presence of heterogeneity in live weights of finished pigs after 105 days of fattening.

Table 3.5 Simulated growth performance and nutrient excretion results of growing-finishing pigs (23 kg to slaughter weight; simulated with InraPorc®)

Parameters	Reference case[1]	Macaúba case[1]	Co-products case[1]
Total feed intake (kg/pig) [2]	246.48 (26.52)	252.12 (27.12)	252.12 (27.12)
Average daily gain (g/day)	880.85 (131.40)	880.85 (131.40)	880.85 (131.40)
Feed conversion ratio (kg feed/kg gain) [2]	2.66 (0.45)	2.73 (0.46)	2.73 (0.46)
Final live weight (kg/pig)	115.49 (13.72)	115.49 (13.72)	115.49 (13.72)
Protein mass (kg/pig)	17.88 (2.70)	17.88 (2.70)	17.88 (2.70)
Lipid mass (kg/pig)	27.98 (4.55)	27.98 (4.55)	27.98 (4.55)
Nutrient excretions (kg/pig)			
Volatile solids	18.46 (1.99)	27.40 (3.01)	26.33 (2.87)
Nitrogen	3.66 (0.48)	3.78 (0.49)	3.82 (0.49)

Figures in parentheses refer to standard deviations.
[1] A corn-soybean meal, macaúba kernel cake and co-products based finishing diets were used in the reference, macaúba and co-products cases, respectively. Diets of sows, piglets and growing pigs, which were the same in the three cases, were considered. Net energy intakes were the same in the three cases. [2] Including average feed consumption by lost pigs during fattening.

The details of feed intake and cost, and GHG emissions from feed production and manure at the different stages of finishing a pig are summarised in Table 3.6. The total feed intake in the growing-finishing stage (Table 3.5) can be decomposed into the growing stage (117 kg) and the finishing stage 129 kg for the reference case and 135 kg for the alternative cases. Although feed intake is higher in the finishing stage than in the growing stage, feed cost and emissions are comparable between the two stages as larger volumes of high quality ingredients (e.g. soybean oil) and supplements (e.g. lysine) are used in the growing diet (Table 3.1), which raise feed cost and GHG emissions. Feed costs and emissions of sows, piglets and growing pigs are the same under the three cases. Although the unit prices of finishing diets (R$/kg feed) are lower for the alternative cases (0.50 for macaúba and 0.56 for co-products cases) than the reference case (0.57), the higher feed intakes in the alternative cases (135 kg) than the reference case (129 kg) reduced (and even outweighed in the co-products case) the price advantages. Similarly, the higher feed intakes in the alternative cases reduced their environmental cost advantages from feed production although the unit GHG emissions (kg CO_2-eq per kg feed) are lower for the alternative finishing diets (0.419 for macaúba and 0.475 for co-products cases) than for the reference diet (0.514). Emissions from manure are higher for the alternative cases than the reference case due to the higher volumes of volatile solids (Table 3.5) following from the higher fibre concentrations, and higher feed intakes. The avoided emissions, due to the replacement of artificial fertiliser by manure, are comparable among the three cases (refer to Appendix 3A, Table 3.A3 for details).

Table 3.6 Summary of feed intake (kg), feed cost (US$) and greenhouse gas (kg CO_2-eq) emissions from feed production and manure per finished pig at different stages of production

			Greenhouse gas emissions		
	Feed use	Feed cost	Feed	Manure	Avoided[1]
Reference case					
Sows	48.0	8.8	26.5	8.0	1.2
Piglets	25.0	9.2	14.3	4.1	1.1
Growing pigs	117.2	22.5	67.5	24.3	7.0
Finishing pigs	129.3	22.1	66.5	25.2	7.2
Total	319.5	62.7	174.8	61.6	16.5
Macaúba case					
Sows	48.0	8.8	26.5	8.0	1.2
Piglets	25.0	9.2	14.3	4.1	1.1
Growing pigs	117.2	22.5	67.5	24.3	7.0
Finishing pigs	134.9	20.2	56.5	45.9	7.5
Total	325.1	60.8	164.8	82.3	16.8
Co-products case					
Sows	48.0	8.8	26.5	8.0	1.2
Piglets	25.0	9.2	14.3	4.1	1.1
Growing pigs	117.2	22.5	67.5	24.3	7.0
Finishing pigs	134.9	22.7	64.1	43.5	8.3
Total	325.1	63.2	172.4	79.9	17.6

[1] Avoided emission of greenhouse gases due to the replacement of artificial fertilizer with manure

Annual farm level revenues, costs, private profit and social profit are presented in Table 3.7.

Table 3.7 Revenues, costs, private profit and social profit per year for a typical Brazilian farrow-to-finish pig farm (×1000 US$)

Parameters	Reference case	Macaúba case	Co-products case
Revenues			
Sales of finished pigs	3,504 (539)	3,504 (539)	3,504 (539)
Sales of culled gilts and sows	72 (6)	72 (6)	72 (6)
Total revenue	3,576 (539)	3,576 (539)	3,576 (539)
Variable costs			
Sows and gilts costs	688 (23)	688 (23)	688 (23)
Feed cost of fattening pigs	1,819 (219)	1,757 (208)	1,837 (218)
Non-feed costs of fattening pigs	205	205	205
Total variable costs	2,712 (234)	2,650 (224)	2,730 (233)
Total fixed costs	305	305	305
Total costs	3,017 (234)	2,955 (224)	3,035 (233)
Private profit	559 (468)	621 (468)	541 (468)
Environmental cost of feed	263 (22)	248 (20)	260 (21)
Net return from manure			
Environmental cost of manure	93 (8)	124 (12)	120 (11)
Avoided environmental cost[1]	25 (3)	25 (3)	26 (3)
Fertilizer value of manure	132 (14)	135 (14)	148 (15)
Net return from manure	64 (9)	36 (8)	54 (7)
Social profit	360 (460)	409 (459)	335 (460)

Figures in parentheses refer to standard deviations.
[1] Avoided environmental cost due to the replacement of artificial fertilizer with manure.

Expected private profit per farm per year is about 11% higher for the macaúba case than the reference case, whereas it is about 3% lower for the co-products case. This difference is due to the differences in feed cost (Table 3.6). The environmental cost of feed per farm per year is about 6% lower for the macaúba case and 1% lower for the co-products case than the reference case. The environmental cost of manure is about 33% higher for the macaúba case and 29% higher for the co-products case compared with the reference case. This increase is due to the higher fibre concentrations in the alternative diets which results in higher methane emissions (Rigolot *et al*., 2010) and to the higher feed intakes in the alternative cases. Social profit is about 14% higher for macaúba case compared to the reference case whereas it is about 7% lower for the co-products case. However, net environmental costs (i.e. environmental cost of feed minus net return from manure) are higher under the alternative cases (by about 7% in the macaúba case and by 4% in the co-products case) than under the reference case.

Results in Table 3.7 also show that social profit is about 36% lower than private profit for the reference case, 34% lower for the macaúba case and 38% lower for the co-products case. Although the net returns from manure are positive, social profits are lower than private profits due to the environmental costs of feeds. When the net return from manure is excluded from the model (i.e. if we include the environmental cost of only feed), social profit is about 47% lower than private profit in the reference case, 40% lower in the macaúba case and 48% lower in the co-products case. The variabilities of farm profits, measured by the standard deviations, are high relative to the mean values (e.g. with CV between 75% and 87% for private profits). The variability of profits is comparable among the three cases as the higher feed intakes in the alternative cases compensate the small differences in the volatility of prices of finishing pig diets.

The result of the sensitivity analysis show that a 14% increase in the price of macaúba kernel cake based finishing pig diet results in about 15% decrease in profits under the macaúba case, which makes the profit in the macaúba case about 6% lower compared with the reference case. Private profits for the reference and macaúba cases are equal when the price of the macaúba kernel cake based diet increases by 9.2% (given other parameters constant).

3.4 Discussion

The expected private profit of pig farming in Minas Gerais (Brazil) is 558,908 US$ per farm per year. This is equivalent to a profit of 0.14 US$ per kg live weight pig. However, this profit does not account for the costs of feed manufacturing (i.e. grinding and pelleting) and feed transport between the feed mill and pig farm. The profit computed in this paper is slightly higher than the profit computed based on the cost of production from Embrapa Swine and Poultry Centre for Minas Gerais. Using the average cost of production (2006-2015) (Embrapa swine and poultry centre, 2016) and the average selling price of finished pigs (2006-2015) in Minas Gerais (www.agrocotacoes.com.br), average profit per kg live weight was 0.13 US$. The difference could be attributed to the use of different input values (e.g. feed prices due to difference in diet compositions).

The introduction of stochasticity in the BEFM provides insights into the distribution of the profit of pig farming. Although the expected profit of pig farming in Minas Gerais is positive (the probability of making a loss being about 11%), its variability is substantial due to the stochasticity of prices and biological parameters. Price volatility affects investment decisions, production levels, profitability, and ultimately long run economic growth. Rezitis and

Stavropoulos (2009) showed that pork price volatility has a negative effect on production levels. Variability in the economic and biological parameters deters farmers from adopting innovations for increasing productivity and production. Therefore, stabilization of pork and feed prices, and reducing performance differences between pigs contribute to the improvement of the pig industry via increased investments.

The use of co-products in the diets of pigs might help to hedge against rising and fluctuating prices of the current system, which mainly depend on high quality feed ingredients (i.e. corn and soybean meal). In the current study, due to lack of historical prices on co-products, we assumed that the variabilities of the three finishing diets follow the same trend. However, in practice the prices of co-products might not perfectly be correlated with the prices of corn and soybean meal. If that is the case, pig producers may use co-products to reduce the impact of price volatility of the conventional ingredients. The use of co-products in the diets of pigs including macaúba kernel cake has also other benefits that are not included in this study. For example, the use of co-products reduces the competition for cropland between the feed and food sectors and thereby contributes to food security by making available cropland for food crops production (Ali *et al*., 2017).

In the current study, the use of co-products in the diets of pigs is limited to the finishing stage (70 kg to slaughter weight) due to the low digestibility of co-products and higher digestive capacity of finishing pigs than piglets and growing pigs. The finishing stage is the most important stage of pig production since 40% of feed is used in this stage (and feed conversion ratio worsens with the age of finishing pigs) which raise feed cost and emission of GHGs. The associated land use for feed production is also large compared to other stages of production. Research has been done to improve the digestibility of low quality ingredients (e.g. Omogbenigun *et al*., 2004) and to improve the digestive capacity of pigs via breeding that might increase the use of co-products in different stages of production. The supply of co-products is also limited compared with conventional ingredients (e.g. corn and soybean meal). Therefore, the current step that we followed (replacing at the finishing stage) would already be a substantial change.

To build the BEFM, a number of assumptions and simplifications were needed as with any model. Additional social costs can be thought of as well as additional social benefits. The only environmental cost included was that of GHGs emission from feed production and manure while excluding other environmental impacts and GHGs emission from other stages of production. The fertiliser value of manure was also included. With only these environmental costs and fertiliser value of manure included, the social profit of pig farming is 34% to 38% lower than the private profit implying that the society is incurring costs for the damages caused by emission of GHGs, which are not internalised by the producer. The inclusion of other environmental costs (e.g. acidification, eutrophication and GHGs emission from other stages of production) would further reduce the social profit. However, the current overestimation of social profit does not affect the comparison of the effect of innovations on private and social profits since the directions of changes remain the same. The emphasis on feed production and manure is reasonable, as these are the main contributors to environmental problems in the pig production chain (Nguyen *et al*., 2012; Cherubini *et al*., 2015).

The net return from manure, the difference between its value as a fertiliser and its net environmental cost, was included in the BEFM. The net return from manure was positive in all three cases. The fertiliser equivalent value of manure was calculated by using the prices of artificial fertilisers. Although we used a lower efficiency rate for the N fertiliser (75%), the use of the prices of artificial fertilisers could still overvalue manure as the efficiency, and convenience for transportation and application are lower for manure compared with artificial fertiliser. Therefore, the results of the social profits are overvalued following from the use of prices of artificial fertiliser for manure. We also did not take into account processes beyond manure storage such as emissions during transport and field application. The use of manure as a fertiliser helps to improve the soil structure (by improving organic matter). We also did not consider this advantage of manure over artificial fertiliser. Results will be affected if these costs and benefits are considered. Finally, availability of land for manure application close to a pig farm is a requirement in order to realise the benefits of manure as a fertiliser. This will not always be the case.

3.5 Conclusions

The objective of this paper was to develop a stochastic bio-economic farm model for assessing the impact of innovations on private and social profits of a typical farrow-to-finish pig farm. The empirical application focused on assessing the impact of using co-products in the diets of finishing pigs on private and social profits of a Brazilian pig farm. The developed model is a generic model that can be adapted to other regional production systems (e.g. feeding system, manure management) to assess the impact of a wide range of innovations on private and social profits. For a typical Brazilian farrow-to-finish pig farm, social profits are (34%–38%) lower than private profits. The use of co-products does not always result in higher profits compared with the reference case. Private and social profits are higher for the macaúba case (11% and 14%, respectively); whereas they are lower for the co-products case (3% and 7%, respectively) than the reference case. Other benefits of co-products (e.g. improving land use efficiency and reducing emissions from land use change) should also be taken into account to utilise co-products. The coefficient of variation of farm profits is between 75% and 87% in the three cases.

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Appendix 3A Supplementary material

Appendix 3.A1 Equations used to calculate costs and returns

This section presents the equations used to calculate the costs and returns of sows and fattening pigs for a typical farrow-to-finish farm.

Cost of gilts and sows per farm

$$N_{RG} = RR \times N_{S,stock}$$

$$RR = NF_{S/y}/average\ parity\ at\ removal$$

$$NF_{S/y} = 365/I_{farr}$$

$$I_{farr} = GL + LL + I_{wean-oest} + XD$$

$$Age_{RG,mat} = Age_{RG,1Oes} + 21 \times (NOM - 1)$$

$$I_{rep-conc} = Age_{RG,mat} - Age_{RG,pur} + XD$$

$$TNRGD = N_{RG} \times I_{rep-conc} \times [1 - 0.5 \times (Cul_{RG} + M_{RG})]$$

$$TC_{RG} = TNRGD \times [ADFU_{RG} \times PF_S + DNFC_{RG}] + N_{RG} \times [PC_{RG} + Cul_{RG} \times MC]$$

$$N_s = N_{RG} \times (1 - Cul_{RG} - M_{RG}) + N_{S,stock} \times (1 - Cul_S - M_S) = N_{S,stock}$$

$$\mathrm{SC}_{\mathrm{farm/year}} = NF_{S/y} \times N_s \times [1 - 0.5 \times (Cul_S + M_S)] \times (FR \times SD \times \mathrm{SC}_{\mathrm{dose}} + SR \times SD \times \mathrm{SC}_{\mathrm{dose}})$$

$$\begin{aligned} TC_S = \{&FR \times NF_{S/y} \times N_s \times (1 - 0.5 \times M_S) - (1 - 0.5 \times Cul_S) \\ &\times [I_{farr} \times (ADFU_{S,ges} \times PF_S + DNFSC_S) + LL \times (ADFU_{S,lac} - ADFU_{S,ges}) \\ &\times PF_S]\} \\ &+ \{0.5 \times (I_{ins-cul} + I_{wean-cul}) \times Cul_S \times N_s \times (ADFU_{S,ges} \times PF_S + DNFSC_S)\} \\ &+ \{N_s \times Cul_S \times MC\} + \{\mathrm{SC}_{\mathrm{farm/year}}\} \end{aligned}$$

Return from gilts and sows per farm per year

$$\mathrm{Revenue}_{RG} = P_{RG,cul} \times N_{RG} \times Cul_{RG} \times LW_{RG,cul}$$

$$\mathrm{Revenue}_S = P_{S,cul} \times N_s \times Cul_S \times LW_{s,cul}$$

Costs of fattening pigs

$$NBA_{S,Y} = TNB_{S,Y} \times [1 - (piglets\ lost\ during\ birth/TNB)] = NF_{S/y} \times NBA_{S,farrowing}$$

$$NWP_{S,Y} = NBA_{S,Y} \times (1 - PWM)$$

$$NGP_{S,Y} = NWP_{S,Y} \times (1 - M_{GP})$$

$$NFP_{S,Y} = NGP_{S,Y} \times (1 - M_{FP})$$

$$Feed\ cost_{Piglet,S,Y} = NWP_{S,Y} \times PF_{piglet} \times ADFU_{piglet} \times \{(BW_{f,piglet} - BW_{birth} - ADG_{Prewean} \times LL)/ADG_{piglet}\}$$

$$Feed\ cost_{GP,S,Y} = NWP_{S,Y} \times (1 - 0.5 \times M_{GP}) * PF_{GP} \times ADFU_{GP} \times \{(BW_{f,GP} - BW_{f,Piglet})/ADG_{GP}\}$$

$$= NWP_{S,Y} \times (1 - 0.5 \times M_{GP}) \times PF_{GP} \times FCR_{GP} \times (BW_{f,GP} - BW_{f,Piglet})$$

$$Feed\ cost_{FP,S,Y} = NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times PF_{FP} \times ADFU_{FP} \times \{(LW_{swt} - BW_{f,GP})/ADG_{FP}\}$$

$$= NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times PF_{FP} \times FCR_{FP} \times (BW_{swt} - BW_{f,GP})$$

$$Feed\ cost\ _{fattening,farm} = FR \times N_s \times (Feed\ cost_{Piglet,S,Y} + Feed\ cost_{GP,S,Y} + Feed\ cost_{FP,S,Y})$$

$$Lab\ cost_{fattening,S,Y} = NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times Lab\ cost_{fattening}$$

$$Vet\ cost_{fattening,S,Y} = NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times Vet\ cost_{fattening}$$

$$Ener\ cost_{fattening,S,Y} = NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times Ener\ cost_{fattening}$$

$$OVC_{fattening,S,Y} = NGP_{S,Y} \times (1 - 0.5 \times M_{FP}) \times OVC_{fattening}$$

$$TVC_{fattening,farm} = Feed\ cost\ _{fattening,farm} + [FR \times N_s \times (Lab\ cost_{fattening,S,Y} + Vet\ cost_{fattening,S,Y} + Ener\ cost_{fattening,S,Y} + OVC_{fattening,S,Y})]$$

$$TC_{farm} = TC_{RG} + TC_S + TVC_{fattening,farm} + TFC_{farm}$$

Returns from fattening pigs

$$Revenue_{Fattening\ pigs,S,Y} = NFP_{S,Y} \times P_{LW,FP} \times LW_{swt}$$

$$Revenue_{Fattening\ pigs/farm} = FR \times N_s \times NFP_{S,Y} \times P_{LW,FP} \times LW_{swt}$$

Private and social profits

$$\text{Private profit (US\$/farm/year)} = \text{ER} \times \left(Revenue_{Fattening\ pigs/farm} + \text{Revenue}_{RG} + \text{Revenue}_{S} - TC_{farm}\right)$$

$$Environmental\ cost\ of\ feed\ \text{(US\$/farm/year)} = FR \times N_s \times NFP_{S,Y} \times SP \times \left(TFU_S \times EF_S + TFU_{piglet} \times EF_{piglet} + TFU_{GP} \times EF_{GP} + TFU_{FP} \times EF_{FP}\right)$$

$$\text{Social profit (US\$/farm/year)} = \text{Private profit (US\$/farm/year)} - Environmental\ cost\ of\ feed\ \text{(US\$/farm/year)} + Net\ return\ from\ manure\ \text{(US\$/farm/year)}$$

$Net\ return\ from\ manure$: Refer to Table 3.A3 for the calculations.

Abbreviations

$ADFU_{piglet}$: average daily feed usage of piglets (kg/d)

$ADFU_{RG}$: average daily feed usage of replacement gilt (kg/day)

$ADFU_{S,ges}$: average daily feed usage of gestating sow (kg/day)

$ADFU_{S,lac}$: average daily feed usage of lactating sow (kg/day)

$Age_{RG,1Oes}$: age of replacement gilt at 1st oestrus (days)

$Age_{RG,mat}$: age of replacement gilt at first mating (days)

$Age_{RG,pur}$: age of replacement gilt at purchase/selection (days)

$BW_{f,piglet}$: final body weight of piglet (kg)

Cul_{RG}: culling rate of replacement gilts until mating per year in decimal

Cul_S: culling rate of sows in decimal

$DNFC_{RG}$: daily replacement gilt non feed cost (labour, energy, transport, veterinary, maintenance and repairs, etc.) (R$/day)

$DNFSC_S$: daily sow non-feed and non-semen costs (labour, energy, transport, veterinary, maintenance and repairs, etc.) (R$/day)

EF_{FP}: Greenhouse gas emission factor of finishing pig feed (kg CO_2-eq/kg feed)

EF_{GP}: Greenhouse gas emission factor of growing pig feed (kg CO_2-eq/kg feed)

EF_{piglet}: Greenhouse gas emission factor of piglet feed (kg CO_2-eq/kg feed)

EF_S: Greenhouse gas emission factor of sow feed (kg CO_2-eq/kg feed)

$Ener\ cost_{fattening}$: cost of energy during fattening per finished pig (R$)

$Ener\ cost_{fattening,S,Y}$: total cost of energy during fattening per sow per year (R$)

$Feed\ cost\ _{fattening,farm}$: total feed cost of fattening pigs per farm per year (R$)

$Feed\ cost_{FP,S,Y}$: total finishing pig feed cost per sow per year (R$)

$Feed\ cost_{GP,S,Y}$: total growing pig feed cost per sow per year (R$)

$Feed\ cost_{Piglet,S,Y}$: total piglet feed cost per sow per year (R$)

I_{farr}: farrowing interval (days)

$I_{ins-cul}$: number of days between 1st insemination and culling of sows (days)

$I_{rep-conc}$: interval between purchase/selection of replacement gilt and conception (days)

$I_{wean-cul}$: number of days between weaning and culling (days)

$I_{wean-oest}$: interval between weaning and oestrus (days)

$Lab\ cost_{fattening}$: cost of labor during fattening per finished pig (R$)

$Lab\ cost_{fattening,S,Y}$: total cost of labor during fattening per sow per year (R$)

$LW_{RG,cul}$: live weight of gilt at culling (kg/gilt)

$LW_{S,cul}$: live weight of sow at culling (kg/sow)

LW_{swt}: live weight of finished pig at slaughter (kg/pig)

M_{FP}: mortality rate during finishing period (from 70kg to slaughter) in decimal

M_{GP}: mortality rate during growing period (from weaning to 70 kg) in decimal

M_{RG}: mortality rate of replacement gilts (before conception) in decimal

M_S: mortality rate of sows in decimal

$NBA_{S,farrowing}$: number of piglets born alive per sow per farrowing

$NBA_{S,Y}$: number of piglets born alive per sow per year

$NFP_{S,Y}$: number of finished pigs per sow per year

$NF_{S/y}$: number of farrowing per sow per year

$NGP_{S,Y}$: number of growing pigs transferred to finishing phase per sow per year

N_{RG}: number of purchased/selected replacement gilts per farm per year

$N_{S,stock}$: number of existing sows per farm (sows with at least one farrowing)

N_S: number of sows per farm including pregnant gilts

$NWP_{S,Y}$: number of piglets weaned per sow per year

$OVC_{fattening}$: other variable costs (maintenance-repairs, transport, marketing, others) during fattening per finished pig (R$)

$OVC_{fattening,S,Y}$: total other variable costs (maintenance-repairs, transport, marketing, & others) during fattening per sow per year (R$)

PC_{RG}: purchasing cost of replacement gilt/opportunity cost of selected gilt (R$/gilt)

PF_{FP}: finishing pig feed price (R$/kg)

PF_{GP}: growing pig feed price (R$/kg)

PF_{piglet}: piglet feed price (R$/kg)

PF_S: price of sow and gilt feed (R$/kg)

$P_{LW,FP}$: price of finished pigs (R$/kg live weight)

$P_{RG,cul}$: price of culled replacement gilt (R$/kg live weight)

$P_{S,cul}$: price of culled sow (R$/kg live weight)

FCR: feed conversion ratio (kg feed/kg gain)

FP: finishing phase

FR: farrowing rate (proportion of sows farrowed) (decimal)

GL: gestation length (days)

GP: growing phase

LL: lactation length (days)

MC: marketing cost of culled gilts/sows (R$/sow)

NOM: number of oestrus at first mating

PWM: pre-weaning mortality rate (decimal)

$Revenue_{Fattening\ pigs/farm}$: total revenue from the sale of finished pigs per farm (R$/farm/year)

$Revenue_{Fattening\ pigs,S,Y}$: total revenue from the sale of finished pigs (R$/sow/year)

Revenue_{RG}: total return from culled gilts (R$/farm)

Revenue_{S}: total return from culled sows (R$/farm)

RR: Annual replacement rate of sows (decimal)

SC_{dose}: semen cost per dose (R$/dose)

SD: semen dose per sow per pregnancy (#)

SP: Shadow price of CO_2 emission (US$/kg)

SR: Service repetition rate (decimal)

TC_{farm}: Total cost of production per farm per year (R$)

TC_{RG}: total cost of replacement gilts per farm per year (R$)

TC_{S}: total cost of sows per farm per year (R$)

TFC_{farm}: total fixed cost per farm per year (R$)

TFU_{FP}: Total feed usage of finishing pigs during the finishing phase (kg/finished pig)

TFU_{GP}: Total feed usage of growing pigs per finished pig (kg/finished pig)

TFU_{Piglet}: Total feed usage of piglets per finished pig (kg/finished pig)

TFU_{S}: Total feed usage of sows per finished pig (kg/finished pig)

$TNB_{S,Y}$: total number of piglets born including piglet loss during birth per sow per year

$TVC_{fattening,farm}$: total variable cost of fattening pigs per farm per year (R$)

$TNRGD$: total number of replacement days for gilts (till conception) (days)

$Vet\ cost_{fattening}$: cost of veterinary during fattening per finished pig (R$)

$Vet\ cost_{fattening,S,Y}$ total cost of veterinary during fattening per sow per year (R$)

XD: extra days open due to anoestrus and failed conception

Table 3.A1 Production indicators, input demands and costs in the piglet production and growing-finishing units

	Piglet production	Growing-finishing	Reference
Production indicators			
Productive sows (#/farm)	1,500	-	Embrapa[1]
Finished pigs (#/sow/year)	-	24.65	Embrapa[1]
Rounds per year	-	2.85	Martins *et al*. (2012)
Finished pigs per round (#)	-	4,000	Martins *et al*. (2012)
Main input demands			
Labour demand	110 sows/person	1,500 fattening pigs/person	Martins *et al*. (2012)
Energy demand (kwh)	164 per sow/year	4.5 kwh/finished pig	Martins *et al*. (2012)
Semen dose per pregnancy (#)	2	-	Martins *et al*. (2012)
Input prices			
Monthly wage (R$)	1,200		
Cost of electricity (R$/kwh)	0.27		iea.sp.gov.br
Cost of semen (R$/dose)	11.71		Embrapa[1]
Cost of production per kg live weight of finished pig (R$)			
Veterinary cost	-	0.05	Embrapa[1]
Other variable costs	-	0.30	Embrapa[1]
Fixed cost	-	0.229	Embrapa[1]
Cost of production (calculated)	***Per sow per year***	***Per finished pig***	
Labour cost (R$)	131.04	3.37	
Semen cost (R$/pregnancy/sow)	23.14	-	
Energy cost (R$)	44.28	1.22	
Veterinary cost[2] (R$)	83.30	2.14	
Other variable costs[2] (R$)	532.34	13.68	
Fixed cost (R$/farm/year)	1,016,073		

R$ = Brazilian Real.

[1] Embrapa Swine and Poultry Centre (http://www.cnpsa.embrapa.br/cias/dados/custo.php).

[2] Assuming that the distribution of these costs between the piglet production and growing-finishing units is similar with the distribution of labour cost between the two units.

Appendix 3.A2 Parameters and equations to calculate CH_4 and indirect N_2O emissions from manure

For the growing and finishing phase, the mathematical models of Dourmad *et al*. (2003) and Rigolot *et al*. (2010) were used to calculate the amounts of volatile solids and nutrient excretions using the different diets.

Volatile solid excretions

$$DM_{Faeces} = FI \times DM_{feed} \times (1 - dC_{DMfeed})$$

$$dC_{DMfeed,GFP} = \left(0.709 + (17.94DE - 0.49NDF - 1.09MM)/DM_{feed}\right)$$

$$OM_{Faeces} = FI \times OM_{feed} \times (1 - dC_{OMfeed})$$

$$dC_{OMfeed,GFP} = \left(0.744 + (14.69DE - 0.50NDF - 1.54MM)/DM_{feed}\right)/\left(OM_{feed}/DM_{feed}\right)$$

$$OM_{biogas} = OM_{Faeces} \times d \times Int_{flushing}/2$$

$$DM_{effluent} = DM_{Faeces} - OM_{biogas} + \left(N_{excretion,urine} - N_{volatisation}\right) \times 17/14$$

$$OM_{effluent} = OM_{Faeces} - OM_{biogas} + \left(N_{excretion,urine} - N_{volatisation}\right) \times 17/14$$

N, P and K excretions

$$total\ N_{excretion} = N_{intake} - N_{retained}$$

$$N_{intake} = \frac{0.001 \times CP \times FI}{6.25}$$

$N_{retained} = difference\ between\ N\ contents\ of\ two\ successive\ body\ weights$. N body weight is computed as (cited in Saintilan *et al*., 2013):

$$N_{BW} = \frac{e^{(-0.9892 - 0.0145 \times LMP)} \times (0.915 \times BW^{1.009})^{(0.7518 + 0.0044 \times LMP)}}{6.25}$$

$$LMP = 72.58 - 43.49 \times \frac{L_{BW}}{EBW}$$

$$EBW = 5.969 \times P_{BW}^{0.944} + 0.854 \times L_{BW}^{0.944}$$

$$N_{excretion,faeces} = \frac{(1 - dC_{CP}) \times 0.001 \times CP \times FI}{6.25}$$

$$N_{excretion,Urine} = total\ N_{excretion} - N_{excretion,faeces}$$

$$P_{excretion} = P_{intake} - P_{retained}$$

$$P_{intake} = FI * 0.001 \times P_{content,feed}$$

$$P_{retained} = 0.001 \times 5.39 \times EBW$$

$$K_{excretion} = K_{intake} - K_{retained}$$

$K_{intake} = FI \times 0.001 \times K_{content,feed}$

$$K_{retained} = \frac{-0.0041 \times EBW^2 + 2.68 \times EBW}{1000}$$

where

CP: Crude protein content of the diet (g/kg)

d: coefficient of degradation of organic matter of manure (decimal, 0.00187: assuming a dry matter of 56g/kg manure and 20 °C storage temperature)

dC_{CP}: digestibility coefficient of crude protein of feed (decimal)

dC_{DMfeed}: digestibility coefficient of dry matter of feed (decimal)

dC_{OMfeed}: digestibility coefficient of organic matter of feed (decimal)

DE: digestible energy content of feed (MJ/kg)

$DM_{effluent}$: dry matter of effluent (kg/pig)

DM_{Faeces}: dry matter content of faeces (kg/pig)

DM_{Feed}: dry matter content of feed (decimal)

EBW: Empty body weight (kg/pig)

FI: feed intake (kg/pig)

GFP: growing-finishing pig

$Int_{flushing}$: Flushing interval of manure from the storage (days) (manure is stored for 120 days in Brazil)

$K_{content,feed}$: K content of diet (g/kg)

$K_{excretion}$: K excretion per pig (kg/pig)

K_{intake}: K intake per pig (kg/pig)

$K_{retained}$: K retained per pig (kg/pig)

L_{BW}: Lipid mass of a pig (kg/pig; obtained from the pig growth model)

LMP: Lean meat percentage (%)

MM: Mineral matter (ash) content of feed (decimal)

NDF: Neutral Detergent Fiber content of feed (decimal)

$N_{excretion,faeces}$: N excretion in the faeces (kg/pig)

$N_{excretion,urine}$: Nitrogen content of urine (kg/pig)

N_{intake}: N intake per pig (kg/pig)

$N_{retained}$: N retained (kg/pig)

$N_{volatisation}$: Nitrogen volatilization coefficient during manure storage (decimal, 0.48 from Intergovernmental Panel on Climate Change (IPCC; 2006) default value for liquid manure management)

OM_{biogas}: organic matter of biogas (kg/pig)

OM_{Faeces}: Organic matter of faeces (kg/pig)

OM_{Feed}: organic matter of feed (decimal)

$OM_{effluent}$: organic matter (volatile solid) of effluent (kg/pig)

P_{BW}: Protein mass of a pig (kg/pig; obtained from the pig growth model)

$P_{content,feed}$: P content of diet (g/kg)

P_{intake}: P intake per pig (kg/pig)

$P_{excretion}$: P excretion per pig (kg/pig)

$P_{retained}$: P retained per pig (kg/pig)

$total\ N_{excretion}$: total N excretion per pig (kg/pig)

Table 3.A2 Parameters and equations to calculate CH_4 and indirect N_2O emissions

Parameters	Sows	Piglets	Growing-finishing pig		
			Ref. case[1]	Maca. case[2]	Co-prod. case[3]
Number of animals (#/finished pig)	0.043[a]	1.05[a]	1.00	1.00	1.00
Duration (days)	142[a]	38[a]	105	105	105
Nutrient excretion (kg/finished pig)					
N	0.199[a]	0.183[a]	3.66	3.78	3.82
P	0.185[b]	0.15[b]	0.54	0.49	0.58
K	0.074[b]	0.06[b]	1.35	1.48	1.74
Manure composition (kg/finished pig)					
N[4]	0.103	0.095	1.90	1.96	1.99
P	0.185	0.15	0.54	0.49	0.58
K	0.074	0.06	1.35	1.48	1.74
Volatile solid (*VS;* kg/finished pig)	3.315[a]	1.653[a]	18.47	27.41	26.33
Potential CH_4 production[5] ($B_{0;}$ M^3 CH4/kg VS)	0.29	0.29	0.29	0.29	0.29
CH_4 conversion factor[5] (*MCF; decimal*)	0.42	0.42	0.42	0.42	0.42
Volatilisation[5] (%)	48	48	48	48	48
Emission factor[5] (*EF; decimal*)	0.01	0.01	0.01	0.01	0.01
CH_4 emissions $=VS\times B_0\times 0.67\times MCF$					
Indirect N_2O emissions =N excretion×Volatilisation×EF× (44/28)					
Greenhouse gas emission from manure (kg CO_2-eq/finished pig)[6]			61.62	82.30	79.92

[1] A corn-soybean meal based finishing diet was used in the reference case.
[2] A macaúba kernel cake based finishing diet was used.
[3] A co-product based finishing diet was used. Diets of sows, piglets and growing pigs, which are common to the three cases, were considered.
[4] Assuming 48% volatilisation during storage (IPCC, 2006).
[5] IPCC (2006).
[6] Including sows' and piglets' emissions.
[a] Cherubini *et al*. (2014).
[b] Diesel *et al*. (2002).

Table 3.A3 Net benefit from manure per case

	Reference case[1]	Macaúba case[1]	Co-prod. case[1]
Avoided fertiliser (kg/finished pig)			
Urea	3.43	3.53	3.57
P_2O_5	4.76	4.48	4.96
K_2O	2.96	3.23	3.76
Prices of artificial fertilisers (R$/kg) [2]			
Urea	1.42	1.42	1.42
P_2O_5	0.88	0.88	0.88
K_2O	1.40	1.40	1.40
Values of avoided fertilisers (R$/finished pig)			
Urea	4.87	5.01	5.06
P_2O_5	4.19	3.95	4.37
K_2O	4.15	4.52	5.26
GWP of avoided fertiliser production (Kg CO_2-eq/ finished pig) [3]			
Urea	12.10	12.45	12.59
P_2O_5	2.57	2.42	2.68
K_2O	1.81	1.97	2.29
Environmental benefit of avoided fertiliser (R$/finished pig) [4]			
Urea	1.81	1.87	1.89
P_2O_5	0.39	0.36	0.40
K_2O	0.27	0.30	0.34
GHG emission from manure (kg CO_2-eq/finished pig)	61.62	82.30	79.92
Environmental cost of manure (R$/finished pig) [4]	9.24	12.34	11.98
Net benefit from manure (R$/finished pig)	6.44	3.67	5.34

GWP, global warming potential; GHG, greenhouse gas.

[1] A corn-soybean meal-, a macaúba kernel cake- and a co-products-based finishing diets are used in the reference, macaúba and co-products cases, respectively. Diets of sows, piglets and growing pigs, which are common to the three cases, are considered.

[2] 2015 market prices in MG (www.conab.gov.br).

[3] Using emission factors of fertiliser production from Kool *et al*. (2012).

[4] Using the shadow price of CO_2 emission (US$0.045/kg) and the 2015 exchange rate (R$3.33/US$).

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Chapter 4

Effects of incorporating environmental cost and risk aversion on economic values of pig breeding goal traits

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Summary

Economic values of traits, accounting for environmental impacts and risk preferences of farmers, are required to design breeding goals that contribute to both economic and environmental sustainability. The objective of this study was to assess the effects of incorporating environmental costs and the risk preferences of farmers on the economic values of pig breeding goal traits. A breeding goal consisting of both sow efficiency and production traits was defined for a typical Brazilian farrow-to-finish pig farm with 1,500 productive sows. A mean-variance utility function was employed for deriving the economic values at finishing pig level assuming fixed slaughter weight. The inclusion of risk and risk aversion reduces the economic weights of sow efficiency traits (17%) while increasing the importance of production traits (7%). For a risk neutral producer, inclusion of environmental cost reduces the economic importance of sow efficiency traits (3%) while increasing the importance of production traits (1%). Genetic changes of breeding goal traits by their genetic standard deviations reduce emissions of greenhouse gases, and excretions of nitrogen and phosphorus per finished pig by up to 6% while increasing farm profit. The estimated economic values could be used to improve selection criteria and thereby contribute to the sustainability of pig production systems.

Keywords: Bio-economic model; economic values; environmental impact; pigs; risk aversion

4.1 Introduction

Livestock production causes major environmental impacts following from emissions to air, water and soil (De Vries & De Boer, 2010). The impact is expected to increase with a growing world population and demand for animal proteins. The growing human and livestock populations require increased production of food and feed, which results in increased competition for the use of scarce resources such as cropland, fossil fuel and water (Garnett, 2009). Pig and poultry diets heavily rely on cereals and oilseeds, which can also be used for direct human consumption. To reduce the environmental impacts of pig production systems, several feeding and management practices have been proposed such as use of co-products and locally produced ingredients, diet optimization (e.g. use of low protein ingredients complemented with amino acids) and precision feeding (i.e. meeting the nutrient requirements of individual pigs as accurately as possible). Environmental impacts of pig production can also be reduced through genetic improvement of animals. Genetic improvement has been an effective way to improve productivity and efficiency of pig production. As Wall *et al*. (2010) illustrated, environmental impacts of livestock production can be reduced in broad breeding goals by indirect selection on correlated traits of animal productivity and efficiency. An improvement in feed efficiency, for example, reduces nitrogen excretion of fattening pigs (Shirali *et al*., 2012). An improvement of feed efficiency reduces the production of effluent per unit of product and reduces emission associated with feed production.

The focus of pig breeding programs has been on the genetic improvement of economically important production and reproduction traits such as growth rate, feed conversion ratio, lean meat and piglet production (Kanis *et al*., 2005). Such traits are commonly weighted by their economic values (EVs), which are estimated as the change in profit due to a one unit change in the value of a trait keeping all other traits constant (e.g. Brascamp *et al*., 1985). The EVs are derived from private profit equations or bio-economic models which typically reflect only private costs and benefits, i.e. only costs paid by producers and benefits which accrue to producers. They exclude external costs such as environmental costs, which are associated with damage to humans, ecosystems and resources following from emissions (Field & Olewiler, 2005; Nguyen *et al*., 2012). However, the development of a sustainable production chain requires a complete reflection of the real cost of a product to the society on the final price (Nguyen *et al*., 2012). The future pig production system is expected to implement environmentally sustainable practices due to several increasing push (e.g. regulations) and pull factors (e.g. growing consumer demand for sustainable pork). Through regulations, producers might be obliged or subsidised to internalise their emissions (e.g. via investment on pollution abatement technologies) or might be taxed for the damages caused to the society. For example, about 7 Giga ton CO_2-eq (13% of annual global greenhouse gas (GHG) emission) was covered by different carbon pricing instruments (e.g. carbon taxes and emission trading schemes) in different parts of the world in 2016[1]. The design of breeding goals that contribute to both the economic and environmental sustainability of pig production requires models in which the calculation of EVs accounts for the environmental costs. Previous literature, derived EVs of traits for dairy cattle (Wall *et al*., 2010) and beef cattle (Åby *et al*., 2013) by considering GHG emission costs. However, to the best of our knowledge, there are no studies that accounted for the GHG emission costs in the derivation of EVs for pig breeding goal traits by monetizing emission of GHGs.

Traditionally, EVs of traits are derived from the aforementioned private profit equations or bio-economic models of commercial pig farmers without taking into account their risk preferences or implicitly assuming that farmers are risk neutral. However, there is substantial evidence that agricultural producers are risk averse (e.g. Gunjal and Legault, 1995). As the decision making process of farmers depends crucially on their risk preferences when faced with an uncertain decision, risk and risk preferences need to be taken into account properly. Price volatility is one of the sources of risk in agriculture, and deters farmers from investing in innovations (e.g. genetics) for increasing productivity and production, which in turn influences farm profit. Therefore, EVs of traits should be derived from the utility functions of farmers (e.g. mean-variance utility functions) which take into account not only expected profit, but also the associated risk.

In light of the foregoing discussion, the objective of this study was to assess the effects of incorporating environmental costs and risk preferences of producers on EVs of pig breeding goal traits. The study first proposes a method for integrating environmental costs and risk preferences of producers into the derivation of EVs of traits and applies this to the case of Brazilian farrow-to-finish pig production. Brazil is the fourth largest producer and exporter of pork in the world (USDA, 2014). The pig industry has faced rising feed cost (Embrapa Swine and Poultry Centre, 2016) and environmental problems such as emission of GHGs (Cherubini *et al*., 2015). Feed cost accounts for more than 75% of the total cost of pork production (Embrapa Swine and Poultry Centre, 2016). Furthermore, Brazilian pork and feed prices fluctuate over time. The coefficients of variation of annual selling price of finished pig and feed cost over the period 2006-2015 in Minas Gerais (Brazil) were about 24% and 20%, respectively (Embrapa Swine and Poultry Centre, 2016). A breeding goal that contributes to reducing environmental impacts, and the impacts of increasing feed cost and fluctuation of prices is required to breed for future production systems.

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[1] We refer to the World Bank (2016) for an overview of available carbon pricing instruments implemented to limit GHG emission and carbon prices in different countries.

The remainder of the paper is structured as follows. First, it presents the stochastic bio-economic farm model and the mean-variance utility function that was employed to derive the EVs. Then, the procedure followed to incorporate environmental costs in the derivation of EVs is discussed. This is followed by the presentation of the choice of breeding goal traits and how the EVs are estimated. Finally, results are presented followed by discussion of main findings.

4.2 Materials and methods

This section introduces the bio-economic model that was used to compute EVs of traits, while accounting for environmental costs and farmer's risk preferences.

4.2.1 The bio-economic model

Economic, biological and bio-economic approaches are the three main approaches for estimating EVs (see Nielsen *et al*. (2014) for an overview). The *economic approach* is based on a simple profit equation by identifying traits associated with the returns and costs of pig production. The economic approach does not take into account the physiological impacts of a change in a trait. On the other hand, the *biological approach* uses information on the physiological characteristics of pigs, neglecting the economic impact of a change in the value of a trait. A trait which could be improved using the biological approach might not contribute to profitability. The *bio-economic approach* combines both the economic and biological approaches to define a breeding goal. Bio-economic models are increasingly used to estimate EVs of breeding goal traits as they provide a more accurate description of production systems than profit or biological models (e.g. De Vries, 1989; Houška *et al*., 2004).

This study employed a stochastic bio-economic farm model for a typical Brazilian farrow-to-finish pig farm with 1,500 sows to simulate farm performance (Ali *et al.*, 2017a). In Minas Gerais (southeast of Brazil, where farrow-to-finish production system is mainly practiced), the size of farms vary significantly ranging from 50 sows to more than 5,000 sows. We assume that the typical farm in our model owns 1,500 productive sows with annual replacement rate of 45% (Martins *et al*., 2012). Embrapa Swine and Poultry Centre (www.embrapa.br/en/suinos-e-aves/cias) also assumes 1,500 productive sows per farm in their monthly reports of swine cost of production for the state of Minas Gerais. The model consists of four sub-models: (i) sow, (ii) growing-finishing pig, (iii) manure and (iv) farm. The sow sub-model, which represents the reproduction stage, starts with replacement gilts of 150 days old purchased from a superior herd. After about 70 days, gilts are mated by artificial insemination with purchased semen. Conceived gilts join the sow pool. Females with any problems (e.g. anoestrus, failed conception, leg and udder problems) are culled. The sow production cycle consists of mating, conception, farrowing, lactation and weaning. A sow will be mated or culled depending on her condition and performance after the last weaning. Average farm values per year were used as inputs in the sow sub-model. In line with Brazilian production system, three growth stages were assumed for weaned piglets — piglets (weaning to 23 kg), growing pigs (23-70 kg) and finishing pigs (70-115 kg).

The growing-finishing pig sub-model characterises the growth performance of a 23 kg growing pig until it reaches a constant slaughter weight (115 kg live weight). The InraPorc® model (Van Milgen *et al*., 2008) was used to simulate the growth performance of a growing-finishing pig. Given the inputs of the InraPorc model (e.g. initial age, nutritional values of feed, net energy intakes at 50 kg and 100 kg body weights), the growing-finishing pig sub-model simulates the biological performance of a pig until slaughter weight (e.g. daily growth, daily feed intake and lean meat content). The manure sub-model estimates the amount of excretions of volatile solids and nutrients during the life cycle of a finished pig on the basis of feed intake, nutritional contents of the diet, genotype of the pig and manure management system. It also estimates GHG emissions from manure management and the fertiliser equivalent value of manure. In the farm sub-model, all returns and costs (including environmental costs of feed and manure, and fertiliser equivalent value of manure) were estimated at farm level on the basis of the results of the other sub-models to compute private (farm) profit and social profit. In this study, social profit refers to private profit minus the environmental cost of feed plus the net return from manure. Net return from manure equals fertiliser value of manure plus avoided environmental cost due to avoided artificial fertiliser production minus environmental cost of manure (Ali *et al*., 2017a). We assumed that available farm resources (e.g. buildings and equipment) are optimally used and the farm operates with optimal replacement and culling policies, and feeding practices. The time period taken into account in the model is one year. Therefore, input parameter values represent values per farm, per year. Since all factors of production are variable in the long run and since genetic improvement is also for the long run, fixed costs are treated as variable costs when computing the effect of genetic change on farm profit. More details on the bio-economic model can be found in Ali *et al*. (2017a).

4.2.2 Mean-variance utility function

The profit equation in the bio-economic farm model is re-written into a mean-variance utility function to account for the farmers' risk preferences. Price uncertainty, which is one of the sources of risk, is a standard attribute of agricultural production because of the inherent volatility of input prices and agricultural commodity prices (Moschini & Hennessy, 2001). In the bio-economic farm model, stochasticity of prices and biological variations between growing-finishing pigs were incorporated to estimate the variability of annual profit (Ali *et al*., 2017a). Assuming that a typical Brazilian farrow-to-finish pig producer displays constant absolute risk aversion, her mean-variance utility function can be expressed as (Freund, 1956):

$$U = E(\pi) - 0.5\lambda\sigma_\pi^2 \quad (4.1)$$

where U is mean-variance utility, $E(\pi)$ is expected profit, λ is the Arrow–Pratt coefficient of absolute risk aversion and σ_π^2 is the variance of profit. The Arrow–Pratt coefficient of absolute risk aversion measures the intensity of a producer's aversion to risk. Values of zero, positive and negative imply that a producer is risk neutral, risk averse and risk seeker, respectively. Agricultural economists use several approaches to estimate the risk preferences of producers (i.e. to determine the value of λ) ranging from econometric and mathematical programming techniques to elicitation techniques (see Hardaker *et al*. (2015) for an overview). The values of $E(\pi)$ and σ_π^2 were calculated using the bio-economic farm model introduced above (Ali *et al*., 2017a). Utility decreases with an increase in the coefficient of risk aversion and/or variance of profit (Equation 4.1). We assumed that stochasticity of prices of finished pigs, feeds and replacement gilts, and biological variations between growing-finishing pigs affect the decision making process of a farmer. Table 4.1 presents the expected values, standard deviations and correlation coefficients among the stochastic parameters, which were used to derive $E(\pi)$ and σ_π^2, as described in Ali *et al*. (2017a). The value of σ_π^2 depends on the variances of each parameters (e.g. prices), the co-variances (e.g. co-variance between price of feed and price of finished pig) and the number of finished pigs.

The mean-variance approach is consistent with expected utility maximization under the restrictive assumptions of constant absolute risk aversion or normally distributed profits (Moschini & Hennessy, 2001). To validate the latter assumption, several distributions were fitted to the 2006-2015 price series using @Risk, an add-in for MS Excel (Palisade Corporation, Ithaca, NY). The normal distribution indeed provided the best fit for the price data with their respective means and standard deviations as given in Table 4.1. A normal distribution was also assumed for the biological parameters. Since prices and the biological parameters cannot be negative, the distributions were truncated at zero (i.e. the minimum values are zero). Moreover, prices series were de-trended to remove the effect of the trend term in computing standard deviations and correlation coefficients to avoid systematic variability and associations between prices. Producers take into account the systematic changes in prices when making decisions. However, the random changes cause uncertainty and thereby are a source of risk.

Table 4.1 Mean values, standard deviation (SD) and correlation coefficients among stochastic parameters

Parameters (unit)		Mean	SD	Correlations									
				A	B	C	D	E	F	G	H	I	J
Price of finished pig (R$/kg)	A	3.02	0.290	1.00	0.79	0.21	0.21	0.21	0.21	0.00	0.00	0.00	0.00
Price of replacement gilt (R$/gilt)	B	516.24	27.070		1.00	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00
Piglet feed price (R$/kg)	C	1.23	0.098			1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Growing pig feed price (R$/kg)	D	0.64	0.051				1.00	1.00	1.00	0.00	0.00	0.00	0.00
Sow feed price (R$/kg)	E	0.61	0.049					1.00	1.00	0.00	0.00	0.00	0.00
Finishing pig feed price (R$/kg)	F	0.57	0.045						1.00	0.00	0.00	0.00	0.00
Protein deposition (g/day)	G	131.00	11.00							1.00	0.07	0.33	0.09
Net energy intake at 50 kg body weight (MJ/kg)	H	21.07	2.000								1.00	0.19	0.11
Net energy intake at 100 kg body weight (MJ/kg)	I	28.94	3.000									1.00	-0.03
Precocity per day (decimal)	J	0.01	0.004										1.00

R$, Brazilian real. The 2015 exchange rate (R$/US$) of 3.331 was used for the presentation of results.

Source: Ali *et al*. (2017a).

The actual value of the degree of risk aversion (λ) is not known for Brazilian pig producers. A value of zero implies that a pig farmer is risk neutral whereas a value greater than zero implies that a farmer is risk averse. Higher values of λ implies that producers are more risk averse. A range of values were used for λ based on Anderson and Dillon (1992) who proposed five classes of coefficients of relative risk aversion (r_r): 0.5, hardly risk averse at all; 1.0, somewhat risk averse (normal); 2.0, rather risk averse; 3.0, very risk averse; and 4.0, extremely risk averse. Then, λ is calculated as:

$$\lambda = r_r / w \tag{4.2}$$

where w is wealth. The expected annual profit of the farm— as calculated using the bio-economic farm model introduced above— was used as a proxy for wealth. The annual farm profit of Brazilian farrow-to-finish pig farm US$ 558,908 (Ali *et al.*, 2017a) was used to derive the risk aversion coefficients. For instance, λ is equal to 0.0000018 for 'somewhat risk averse' producer (following Equation 4.2). Although this value of λ looks very small, its effect on utility is large as the variance of a typical Brazilian farrow-to-finish pig farm profit (i.e. 2.19E+11 US$) is big (Ali *et al.*, 2017a). When λ is zero, the mean-variance utility function reduces to the bio-economic profit function.

4.2.3 Environmental costs

Environmental impacts (e.g. global warming potential, acidification, and eutrophication) of pig production can be estimated using life cycle assessment models and the resulting changes in these impacts from a unit change in the value of a trait considered can be calculated. The shadow prices (e.g. the shadow price of CO_2 for global warming potential) can be used to monetise environmental impacts (e.g. Nguyen *et al.*, 2012). Then, by incorporating environmental costs into the bio-economic model, new EVs of the traits can be derived. In this study, as described in Ali *et al.* (2017a), the environmental costs of GHGs emission from feed production and manure management were included in the bio-economic model. Feed production and manure management are the largest contributors to environmental problems in the pork production chain (Cherubini *et al.*, 2015; Nguyen *et al.*, 2012). The environmental impacts of feed production are based on life cycle assessment study of Ali *et al.* (2017b) that estimated emissions of GHGs from extraction of raw materials until the delivery of the feed at a pig farm. Emissions of GHGs from manure management are based on Ali *et al.* (2017a). The emissions were monetised using the 2015 shadow price of CO_2 (US$0.045 per kg CO_2-eq; Ali *et al.*, 2017a). Unlike the stochasticity of prices of inputs and outputs, we assumed that stochasticity of shadow prices of environmental impacts does not affect farmer's decision making as the goal of the farm is to maximize its mean-variance utility, which does not depend on shadow price of CO_2. In this study, the difference between farm (private) profit and environmental cost is referred to as social profit.

4.2.4 Included traits and economic values

Economic weights are often applied to weigh traits in multi-trait economic selection index methodology (Hazel, 1943). To improve the environmental sustainability of Brazilian pig industry by indirect selection (on top of economic sustainability), the main traits that improve productivity and efficiency of pig production should be included in the breeding goal to reduce environmental impacts per kg live weight finished pig. A breeding goal that consists of both sow efficiency and production traits is considered. From sow efficiency traits, number of piglets born alive per litter (NBA), pre-weaning mortality rate (PWM; %) and weaning-oestrus interval (WOI; days) are included. The production traits average daily growth (ADG; g/day) and feed conversion ratio (FCR; kg feed/kg gain) during the growing-finishing stage are included. The included traits are expected to improve the productivity and efficiency of pig production, and thereby reduce environmental impacts per finished pig.

The trait NBA was included in the breeding goal as it affects both revenues (e.g. via the number of finished pigs) and costs (e.g. via feed cost). The trait WOI influences the sow’s reproductive efficiency as it affects the number of farrowing per year. The trait PWM affects profit of the farm as the number of finished pigs depends on the number of weaned piglets per sow. Brazilian pig producers believe that PWM is one of the main factors affecting their farm profitability as it reaches up to 10% (Dias, 2016). Although it could be of interest to consider animal welfare related traits, they were not included, for simplicity, in the breeding goal.

The trait ADG determines the number of days required to reach the slaughter weight thereby affecting costs (including environmental costs). Improved FCR reduces feed cost and emissions of GHGs from feed production and manure management, and excretion of nutrients. Carcass quality indicators (e.g. lean meat content and back fat thickness) are not included in the breeding goal as there is no carcass quality based payment system in Brazil. Although selection on leanness did not directly increase the carcass value in Brazil, it should be included in the selection index as it reduces feed cost.

A fixed number of sows per farm per year (1,500) and a fixed slaughter weight (115 kg) were assumed when assessing the effect of genetic change of traits. The EV of a trait was calculated based on the mean-variance utility function as the ratio of (i) the difference between the utility of a producer after a change in a trait level by its genetic standard deviation in a desired direction and its utility before the genetic change, and (ii) the genetic standard deviation of the trait considered (see Equation 4.3). The resulting change in utility indicates the importance of the trait since genetic standard deviation is an indicator of the rate at which breeding values can be improved. A change in trait level in a desired direction refers to the situation where a change in a trait level results in an increase in utility based on the mean-variance utility function (e.g. increase in ADG and decrease in FCR). The EVs were expressed per finished pig per year. The (absolute) EV of a trait was expressed as:

$$EV_i = \frac{U_{Ai} - U_{Bi}}{trait\ level_{Ai} - trait\ level_{Bi}} = \frac{U_{Ai} - U_{Bi}}{\sigma_{gi}} \quad (4.3)$$

where EV_i is economic value of breeding goal trait i, U is mean-variance utility per finished pig, Ai is after genetic change in trait i and Bi is before genetic change in trait i and σ_{gi} is the genetic standard deviation of trait i. Economic weights of traits (%) were also computed, which refer to the relative importance a trait in the breeding goal. The economic weight of a trait, also known as relative EV, was computed as:

$$EW_i = 100 \times \frac{\sigma_{gi} \times EV_i}{\sum_{i=1}^{n} \sigma_{gi} \times EV_i} \quad (4.4)$$

where EW_i is the economic weight of breeding goal trait i and $i, \dots, n$ refers to the breeding goal traits.

The genetic standard deviations were obtained from the literature (Table 4.2). The EVs were also expressed as elasticities, which represents the % change in utility due to a 1% change in the value of a trait considered in the desired direction. Economists use the term elasticity to measure the responsiveness of a variable (e.g. profit or utility) following from a 1% change in another variable (e.g. a trait level), while other factors remain constant. Traits with higher elasticity imply that utility is more responsive to the genetic change of those traits. The computation of elasticity facilitates communication between economists and animal breeders.

4.3 Results

4.3.1 Key production and economic results before genetic change

Based on the stochastic bio-economic farm model developed in Subsection 4.2.1, key production and economic results were computed for the situation before genetic change. The number of pigs finished per farm per year is about 33,500 pigs with a slaughter weight of 115.5 kg each. The GHG emission (CO_2-eq) is about 7,400 t per year (of which 79% is from feed production and the rest from manure management). The emissions of GHGs from feed production are lower for Brazil compared to estimates for other countries. This is mainly due to the lower emissions associated with Brazilian corn production (Ali *et al.*, 2017b). The annual social profit is about 360,000 US$, and was calculated as annual farm profit (about 559,000 US$) minus the environmental cost of feed (about 263,000 US$) plus the net return from manure (about 64,000 US$; fertiliser value of manure plus avoided environmental cost due to avoided artificial fertiliser production minus environmental cost of manure). The key production and economic results before genetic change for the typical Brazilian farrow-to-finish pig farm are summarised in Appendix 4A (Table 4.A1).

4.3.2 Effects of genetic change of traits on key farm performance indicators

Based on the bio-economic farm model, the effect of genetic change of traits on key farm performance indicators such as number of finished pigs (NFP), feed consumption by fattening pigs (i.e. by piglets, growing and finishing pigs) (Feed), environmental impacts (excretions of GHGs, N and P), and on private and social profits at farm level is presented in Table 4.2. It shows the mechanisms by which changes in trait levels determined changes in the key production and environmental variables, and private and social profits. Changes in the sow efficiency traits in the desired directions increase the number of finished pigs, feed consumption, environmental impacts and (private and social) profits at farm level whereas changes in production traits decrease feed consumption and environmental impacts, and increase profits. The mechanism of increase in private and social profits following from desirable change in traits is as follows. For example, an increase in NBA by its genetic standard deviation results in an increase in the number of finished pigs (by 2,504) which in turn increases feed consumption and environmental impacts (Table 4.2). Private and social profits increase as the return from the additional finished pigs is greater than their costs (including environmental cost in the social profit case). Since a fixed slaughter weight was assumed, an increase in ADG by its genetic standard deviation reduces the age of finishing pig at slaughter. This in turn reduces feed consumption and environmental impacts while farm returns remain constant (assuming that the number of finished pigs remain the same before and after genetic improvement of production traits). When the duration of fattening shortens, more pigs could be finished per year thereby environmental impacts per farm also increase. However, when results are expressed per finished pigs, improvement in both sow efficiency and production traits results in lower environmental impacts per finished pig (as explained in Subsection 4.3.3 below).

From the traits included in the breeding goal, a genetic change in ADG has the highest effect on both private and social profits at farm level (Table 4.2). The traits NBA and FCR are the second most important traits in improving private and social profits, respectively. A desirable change in sow efficiency trait levels results in a lower increase in social profit than private profit. For production traits, however, the increase in social profit is greater than the increase in private profit. Although Brazilian farmers are not paid for carbon reductions currently, they might be paid in the future, for example, with carbon trading schemes (which exist in some countries).

Table 4.2 Effect of genetic change on key farm production and economic results relative to the situation without genetic change for a risk neutral producer (per farm per year)

Traits †	Genetic change (σ_g; trait unit)	ΔNWP ($year^{-1}$)	ΔNFP ($year^{-1}$)	ΔAge (days)	ΔFeed (kg/year)	ΔGHG (kg CO_2-eq/year)	ΔN (kg/year)	ΔP (kg/year)	ΔPrivate profit (US$/year)	ΔSocial profit †† (US$/year)
NBA (per litter)	+0.90‡	+2,635	+2,504	0	+683,103	+467,235	+9,635	+1,726	+105,739	+93,803
PWM (%)	-1.50‡	+579	+550	0	+143,094	+97,940	+1,983	+355	+23,575	+21,046
WOI (days)	-1.00‡	+236	+224	0	+59,811	+40,005	+843	+151	+9,246	+8,241
ADG (g/day)	+50.00§	0	0	-5	-535,795	-366,575	-8,489	-1,538	+108,673	+117,308
FCR (kg/kg)	-0.16§	0	0	0	-522,144	-363,530	-7,378	-1,400	+91,806	+101,835

NWP, number of weaned piglets; NFP, number of finished pigs; Age, age of finished pig at slaughter; Feed, feed consumption of fattening pigs (i.e. piglets, growing and finishing pigs); GHG, net greenhouse gas emission from feed production and manure management (accounting for avoided emission due to the avoided artificial fertiliser); N, nitrogen excretion; P, phosphorus excretion.

† NBA, number of piglets born alive per sow per litter; PWM, pre-weaning mortality rate of piglets; WOI, weaning-oestrus interval; ADG, average daily growth during the growing-finishing stage; FCR, feed conversion ratio during the growing-finishing stage.

†† Social profit refers to private profit minus environmental cost of feed plus net return from manure. Net return from manure equals fertiliser equivalent value of manure plus avoided environmental cost due to avoided fertiliser production following the use of manure as an organic fertiliser minus the environmental cost of manure (for details see Ali *et al*., 2017a).

‡ Rydhmer (2000)

§ Gilbert *et al*. (2007)

4.3.3 Economic values and elasticities of breeding goal traits

The results presented in this section are based on the mean-variance utility function. The last row of Table 4.3 shows the utility of a producer per finished pig before genetic change for risk neutral and risk averse producers, where the standard deviation of farm profit is 467,979 US$ following from stochasticity of prices and biological parameters. As expected, utility decreases with an increase in the degree of risk aversion and variance of profit (following the expression in Equation 4.1). The utility of a 'somewhat risk averse' producer is about 35% lower than the utility of a risk neutral producer (for a constant variance). Utility further decreases with the inclusion of environmental costs of GHGs (again in line with Equation 4.1). Since we found that the (farm and/or social) utilities of 'rather risk averse, very risk averse and extremely risk averse' producers are negative, they are excluded from the analysis as it is unrealistic to continue farming with negative utility. Expected utility theory dictates that any state where utility becomes negative will not be pursued by a rational decision maker.

Table 4.3 presents the effects of incorporating risk preferences of producers on the EVs and economic weights of traits per finished pig by assuming fixed slaughter weight. Since the changes in trait levels were to the desired directions, the EVs of all traits are positive. The EVs are low for all traits, however, within the expected range. The economic importance of sow efficiency traits (except WOI) decreases with an increase in the degree of risk aversion whereas the economic importance of production traits increases. The EV of NBA for a 'somewhat risk averse' producer, for example, is about 17% lower compared with a risk neutral producer. This is because an increase in NBA results in an increase in the number of finished pigs and feed consumption, which in turn increase the variability in revenue and feed cost at farm level. An increase in the variability of profit results in a decrease in utility (via the expression in Equation 4.1). Although the additional finished pigs (from genetic changes) bring additional profit to the farm, they also bring more variability to farm profit thereby decreasing utility per finished pig. However, the decrease in utility due to the increase in variability is partially compensated by the increase in sow's efficiency (e.g. decrease in feed consumption of a sow per its finished pigs) when expressed per finished pig. On the other hand, the EV of FCR for a somewhat risk averse producer is about 6% higher compared with a risk neutral producer. An improvement in FCR reduces feed consumption thereby decreasing variability of feed cost (and variability of profit). A decrease in the variability of profit increases utility (Equation 4.1).

Table 4.3 Absolute economic values of traits (US$ per trait unit per finished pig) and economic weights (%, in brackets) with and without including greenhouse gas emission costs and risk preference of producers for Brazilian farrow-to-finish pig production system

Traits (units) †	Mean trait level (trait unit) ‡	Risk neutral (λ = 0)		Somewhat risk averse (λ = 1.8E-06)	
		SP = 0	SP = 0.045	SP = 0	SP = 0.045
NBA (per litter)	12.02	1.9743	2.0645	1.6325	1.7399
		(21.27)	(20.59)	(17.80)	(17.54)
PWM (%)	8.74	0.2820	0.2964	0.1900	0.2090
		(5.06)	(4.93)	(3.45)	(3.51)
WOI (days)	7.00	0.1633	0.1729	0.1755	0.1885
		(1.96)	(1.92)	(2.13)	(2.11)
Sum reproduction traits (%)		28.29	27.43	23.38	23.16
ADG (g/day)	880.85	0.0649	0.0701	0.0685	0.0734
		(38.85)	(38.84)	(41.49)	(41.10)
FCR (kg/kg) §	2.66	17.1485	19.0219	18.1280	19.9415
		(32.85)	(33.73)	(35.14)	(35.74)
Sum production traits (%)		71.71	72.57	76.62	76.84
Utility before genetic change (US$/finished pig/year)		16.7038	10.7723	10.8484	5.1181

SP = 0 refers to the situation without including the environmental cost of emissions of greenhouse gases. SP=0.045 refers to the situation where greenhouse gas emission costs are included at a shadow price of US$0.045 per kg CO_2-eq.
† Refer to Table 4.2 for the abbreviations of traits.
‡ Change in trait levels were to the desired directions by one unit of genetic standard deviation (i.e. where a change in trait level leads to increase in profit).
§ Including average feed consumption by lost pigs (due to mortality) during fattening.

Table 4.3 also shows the effects of incorporating the environmental costs of GHGs on the EVs and economic weights of pig breeding goal traits per finished pig by assuming fixed slaughter weight. The inclusion of environmental costs at a shadow price of US$0.045 per kg CO_2-eq increases the EVs of both sow efficiency and production traits compared with the situation without environmental costs. The mechanism of the increase in the EVs is as follows. An increase in NBA, for example, increases the number of finished pigs and feed consumption thereby increasing environmental costs and variability of profit at farm level. However, feed consumption and environmental cost of sows remain unchanged during the genetic change (as number of sows is assumed to be fixed). When results are expressed per finished pigs, the effect of the decrease in environmental cost following from sow efficiency improvement on utility per finished pigs outweighs the effect of the increase in variability of profit following from the additional finished pigs (thereby the EV of NBA increases). In other words, although the additional finished pigs (from genetic change) bring more variability to the farm and thereby utility per finished pig decreases, the effect of the decrease in environmental cost per finished pig on utility per finished pig following from the increase in the efficiency of a sow (e.g. decrease in feed consumption of a sow per its finished pigs) is higher. An increase in ADG, on the other hand, results in shorter duration of fattening days, thereby reducing feed consumption (Table 4.2). The reduction in feed consumption reduces feed cost, environmental cost and variance of profit, thereby increasing utility (since number of finished pigs is assumed to be fixed). In terms of economic weights, the economic weight of sow efficiency traits decreases with the inclusion of GHGs emission costs while the weights of production traits increases (Table 4.3).

The elasticities of breeding goal traits with and without accounting for GHG emission costs are presented in Table 4.4. For instance, without accounting for environmental costs, a 1% decrease in PWM and a 1% increase in ADG result in a 0.15% and 3.42% increase in the utility of a risk neutral producer, respectively. The higher the elasticity, the more important the trait is in improving the profit and utility of the producer. With and without GHGs emission costs, the responsiveness of the utility of a somewhat risk averse producer is higher than the responsiveness of a risk neutral producer for both sow efficiency and production traits. The elasticities of traits are higher when environmental cost of GHG emission is included compared with the elasticities without environmental cost for both sow efficiency and production traits for both risk neutral and risk averse producers (Table 4.4).

Table 4.4 Elasticities of traits (%) with and without including greenhouse gas emission costs and risk preference of producers for Brazilian farrow-to-finish pig production system

Traits (unit) ‡	Mean trait level (trait unit) †	Risk neutral (λ = 0)		Somewhat risk averse (λ=1.8E06)	
		SP = 0	SP = 0.045	SP = 0	SP = 0.045
NBA (per litter)	12.02	1.421	2.304	1.809	4.086
PWM (%)	8.74	0.148	0.240	0.153	0.357
WOI (days)	7.00	0.068	0.112	0.113	0.258
ADG (g/day)	880.85	3.422	5.732	5.562	12.632
FCR (kg/kg)	2.66	2.731	4.697	4.445	10.364

SP = 0 refers to the situation without including the environmental cost of emissions of greenhouse gases. SP = 0.045 refers to the situation where greenhouse gas emission costs are included at a shadow price of US$0.045 per kg CO_2-eq.
‡ Refer to Table 4.2 for the abbreviations of traits. † Changes in trait levels were to the desired directions by 1% (i.e. where a change in trait level leads to increase in profit).

The effect of genetic change of traits on emission of GHGs, and N and P excretions per finished pig (assuming a fixed slaughter weight) is summarised in Table 4.5. Genetic improvement of the growth traits (e.g. ADG and FCR) is more effective than genetic improvement of reproductive traits (e.g. NBA) when aiming for a reduction of the environmental impacts per unit of final product (Table 4.5). The last row of Table 4.5 shows the amounts of GHGs emission, and N and P excretions per finished pig before genetic change. A desirable change in trait levels reduces environmental impacts. Genetic improvements of ADG and FCR result in substantial reductions in emissions of GHGs and excretions of N and P compared with genetic improvements of sow efficiency traits.

Table 4.5 Effect of genetic change† on greenhouse gases emission and nutrients excretion per finished pig **(**expressed as % change from values before genetic change)

Traits (unit) ‡	GHG (kg CO_2-eq)	N excretion (kg)	P excretion (kg)
NBA (per litter)	-1.06	-0.34	-1.47
PWM (%)	-0.31	-0.18	-0.42
WOI (days)	-0.13	-0.05	-0.15
ADG (g/day)	-4.98	-6.27	-5.26
FCR (kg feed/kg gain)	-4.94	-5.45	-4.79
Values before genetic change	219.958	4.044	0.874

GHG, greenhouse gases emission from feed production and manure (corrected for avoided emission due to the use manure as an organic fertiliser). N, nitrogen excretion in the manure. P, phosphorous excretion in the manure.

† Genetic changes of traits were to the desired direction by their respective genetic standard deviations (i.e. where a change in trait level leads to increase in profit).

‡ Refer to Table 4.2 for the abbreviations of traits.

4.4 Discussion

4.4.1 The bio-economic model

The bio-economic model that we employed in this study (Ali *et al.*, 2017a) is similar with the model of De Vries (1989) with the following differences. First, the sow sub-model of De Vries (1989) contains more details where the whole life cycle of a sow was simulated whereas we used annual average farm values. Second, our growing-finishing pig sub-model is more detailed compared to De Vries (1989). We incorporated a nutritional pig growth model, InraPorc® model (Van Milgen *et al.*, 2008), to simulate the biological aspects of growing-finishing pigs (23 kg to slaughter weight). The model predicts growth performance of pigs (e.g. daily gain, feed conversion ratio, lean meat) for different types of diets used in the growing and finishing growth stages. The model simulates nutrient partitioning for protein deposition, lipid deposition and for other activities such as maintenance and physical activities. Parameters required for simulating growth performance in InraPorc® model include nutritional values of the different diets used in the different stages, initial age, initial body weight, net energy intakes at 50 kg and 100 kg body weights, final age or final weight, precocity per day and mean protein deposition per day. Third, unlike De Vries (1989), by linking the biological growing-finishing pig sub-model with a mathematical manure sub-model, the amounts of excretions of volatile solids and nutrients (N and P) can be simulated in our manure sub-model considering the different stages of production (sow, piglet, growing and finishing). The resulting volatile solids and excretions of nutrients were used to compute GHGs emission from manure management. As described in Ali *et al*. (2107a), the excretions of nutrients are influenced by feed intake, nutritional content of feed and digestibility of feed. Fourth, unlike De Vries (1989), our model is stochastic that account for volatility of prices and biological variations between fattening pigs. The details of the bio-economic model can be found in Ali *et al*. (2017a).

In this study, since farm is used as a starting profit (and utility) scale of expression, the economic weights (relative economic values) remain the same when expressed per sow or finished pig or kg of product. As Amer and Fox (1992) noted farm profit (in our case farm utility) should always be used as starting point. Once the effect of genetic change on farm profit is computed, division of economic values by the number of breeding sows or finished pig or units of output will yield proportionally equivalent economic weights (Amer and Fox, 1992). Brascamp *et al*. (1985) proposed the 'zero or normal profit' approach to avoid the problem of inconsistent economic weights when derived from different scales of expressions. However, in agriculture, 'normal profit' does not hold as farms, in practice, continue operation while incurring losses for several years.

The derivation of economic weights has been long discussed and there is no single best approach to be applied. Different approaches could estimate quite different values depending on the production system, the economic constraints, the breeding structures, the traits considered in breeding goals and the assumptions made. A breeding goal consisting of three sow efficiency (NBA, PWM and WOI) and two production (ADG and FCR) traits was assumed for the Brazilian farrow-to-finish production system. The economic weight of production traits is greater than the weight of sow efficiency traits. Even if the same model is employed to derive EVs and economic weights, comparison of absolute EVs and their economic weights calculated for different countries is difficult due to several factors including differences in production system, market situation and traits considered in the breeding goals. For example, the relative importance of NBA and feed intake is very different between Germany (where feed price is lower) and Switzerland (Von Rohr, 1998). In the present study, the economic weight of FCR is higher than that of NBA for the Brazilian production system. This is in line with the result of Hanenberg *et al*. (2010) who showed that FCR is the most important trait in Brazil (compared with other countries such as Netherlands, Germany, Spain and USA). They showed that compared to the EVs of Netherlands for litter size and FCR (assuming 100% for Netherlands), the EVs for litter size and FCR are 126% and 84% in Germany, and 91% and 130% in Brazil, respectively. Since the EVs that we derived are based on the Brazilian farrow-to-finish production system, the relative importance of traits might change in other production systems such as the integrated production system in Brazil and other production arrangements in other countries.

Carcass quality (e.g. lean meat and back fat) and societal concern related traits (e.g. animal welfare) are not included in the breeding goal for Brazilian farrow-to-finish production system in the present study. This is due to the fact that there is no carcass quality based payment system and market for animal welfare products in Brazil unlike the situation in developed countries. In practice, breeding programs include carcass quality traits in their breeding-objective traits as these traits reduce feed cost indirectly. Continuous selection for productivity traits (NBA, PWM, WOI, ADG and FCR) may result in undesirable effects on other traits (e.g. deterioration of welfare related traits). However, as economic and production situations are dynamic, breeding goals should also be redefined and EVs need to be updated.

4.4.2 Risk aversion and economic values

Risk and risk preferences are important aspects of farm decision making that are mostly overlooked by studies when deriving EVs of traits. The use of utility functions (e.g. mean-variance) to derive EVs enables to account for risk and risk preferences of producers. The decision of farmers on technology adoption (e.g. genetics) depends on the utility they derive from adopting a certain technology. The use of utility in deriving EVs is more realistic than profit when deriving EVs as it is also linked with the behaviour of humans. Kulak *et al*. (2003), for a two-trait cattle breeding goal, and Peura *et al*. (2016), for a multi-trait blue fox breeding goal, showed that EVs derived from private profit equations or bio-economic models are different from EVs derived from mean-variance utility functions. Large errors in EVs of traits could lead to incorrect breeding-objective traits and might ultimately result in suboptimal or different direction of selection in the long run (Cottle and Coffey, 2013; Kulak *et al*., 2003) which in turn affects farm sustainability. Vandepitte and Hazel (1977) showed that large errors (>50%) in the EV of feed efficiency of pigs can result in up to 76% losses in relative efficiency of a selection index. For some of the traits (e.g. PWM), the results of our study show that there are up to 33% differences between EVs derived with and without including risk preferences of producers. Although there is no ‘true’ value for risk aversion, failing to account the fact that farmers are risk averse results in wrong EVs. Therefore, breeders need to take into account risk and the risk averse nature of producers and adjust their breeding goals accordingly to better serve risk averse producers.

The impact of risk is higher for reproduction traits (e.g. NBA) than for production traits (e.g. ADG) for a fixed number of sows and constant slaughter weight. A desirable change in sow efficiency traits increases risk (i.e. variance of profit) whereas a desirable change in production traits decreases risk. Genetic improvement in pig breeding programs is typically separated in “male” lines, selected predominantly for production traits and “female” lines selected also for reproduction traits. Therefore, genetic improvement of the male line is more important for risk averse producers than female line improvements for Brazilian producers.

The inclusion of risk and risk preferences of producers hardly influences the ranking of both sow efficiency and production traits for Brazilian production system. Peura *et al*. (2016) for a multi-trait blue fox breeding goal and Kulak *et al*. (2003) for a two-trait cattle breeding goal showed that at a higher coefficient of absolute risk aversion (0.02), the absolute EVs and economic weights of traits are greatly affected compared with a situation of lower coefficient of absolute risk aversion (0.0001) (given that variance of profit remain constant). In our study, re-ranking of traits is not observed for both sow efficiency and production traits following the inclusion of risk and risk preferences (although the variance of profit is big) and it could be due to the lower coefficient of absolute risk aversion that we used in the current study (e.g. 0.0000018 for a normally risk averse producer in the current study vs 0.02 in Peura *et al*. (2016) and Kulak *et al*. (2003)). The risk aversion coefficients should be derived empirically for Brazilian producers in order to increase the accuracy of EVs.

The number of discounted expressions (McClintock and Cunningham, 1974) are not considered in this study. The number and time of expressions of traits, however, affect the true economic weights as described by McClintock and Cunningham (1974). Sow efficiency traits are expressed only on females whereas production traits are expressed on both sexes. Moreover, expression of sow efficiency traits are at later ages compared with production traits. The time preference associated with risk is also not considered. The benefits and costs associated with genetic improvement of traits need to be discounted when designing a breeding program. However, the results of this study will not be undermined by the exclusion of number of discounted expressions since the main objective of the study is to show the effect of risk and environmental costs on EVs compared with the traditional EVs (as the discount rate and number of expressions remain the same in all cases).

A mean-variance utility function and a constant absolute risk aversion coefficient are assumed in this study. We employed a mean-variance utility function due to its convenience to capture risk by using variance as its proxy while taking into account risk preferences of producers (via the coefficient of risk aversion). Although other utility functions (e.g. exponential) also allow to take into account risk preferences (e.g. constant absolute risk aversion coefficient for exponential utility function), they do not allow to include a measure of the actual risk (e.g. variance). A mean-variance utility function is consistent with utility maximization theory only in two cases (Moschini & Hennessy, 2001): (1) if the utility function of the producer is quadratic or (2) if profit is normally distributed. A quadratic utility function, however, implies increasing absolute risk aversion. Moreover, profits may not be normally distributed (Hardaker *et al*., 2015) as agricultural prices usually do not follow normal distribution (Deaton & Laroque, 1992). The EVs that we found in this study could change if the coefficient of absolute risk aversion changes with wealth or if profits are not normally distributed. The utility functions of producers (e.g. quadratic vs exponential) need to be known in order to accurately estimate the coefficient of risk aversion and thereby EVs. However, the results of this study will not be undermined by the use of mean-variance utility function as profits are normally distributed in the present case (following from the normal distributions of prices for fixed output as described in Subsection 2.2), which makes it consistent with utility maximization theory.

4.4.3 Environmental cost and economic values

Current pig breeding programs do not account for environmental impacts of pig production systems when defining breeding goals. Currently, direct selection for reduced emissions is not available (Wall *et al*., 2010). This may be due to: (i) the lack of incentive for farmers to reduce emissions (e.g. there is no cost to the farmer for GHG emissions), (ii) the difficulty and costly nature of measurement of emissions in large numbers of animals, and (iii) the impossibility of measurement at all. However, indirect selection for reduced emission via correlated traits (e.g. by improving feed efficiency) is an effective technique as it also improves farm profit. Breeders need to incorporate environmental costs in the derivation of EVs as producers are more responsive to genetic improvement when environmental impacts are considered (refer to Table 4.4). The inclusion of GHG emission cost into the derivations of EVs of traits reduces the relative economic importance of sow efficiency traits slightly while increasing the importance of production traits. In line with the results of the current study, Åby *et al*. (2013) showed that the inclusion of environmental costs of GHGs into the derivation of EVs of traits for the Norwegian cattle production system decreased the relative economic importance of reproduction traits while increasing the importance of production traits. Therefore, genetic improvement of the growth traits (e.g. ADG and FCR) is more effective than genetic improvement of reproductive traits (e.g. NBA) when aiming for a reduction of the environmental impacts per unit of final product for Brazilian producers. Although genetic improvement of sow efficiency traits increases environmental impacts at farm level (Table 4.2), it reduces when expressed per finished pig (Table 4.5). As Van Arendonk (2011) noted, the benefit of genetic improvement of animals on environmental impacts of farms should be expressed per unit of the final product (i.e., kilogram of meat, which is equivalent to finished pig when fixed slaughter weight is assumed as in the case of our study).

Genetic improvements of ADG and FCR result in substantial reductions in emissions of GHGs and excretions of N and P. Excretion of N and P has a positive genetic correlation with FCR and daily feed intake whereas it is negatively correlated with ADG and carcass leanness (Saintilan *et al*., 2013). Shirali *et al*. (2012) also showed that N excretion has a large positive correlation with FCR and a moderate negative correlation with ADG. Similarly, the results of the current study show that excretion of nutrients decreases with an improvement in FCR and increase in ADG. Therefore, by using the new EVs which are derived by taking into account the environmental costs of production systems, breeding programs may pursue alternative breeding goals to meet the future demand for sustainable products.

Re-ranking of traits is not observed for both sow efficiency and production traits following from the inclusion of GHG emission costs. In this study, we considered the environmental cost of only emission of GHGs from feed production and manure management thereby exclude other environmental impacts (e.g. acidification and eutrophication) and emission of GHGs from other chains of pig production. The environmental cost would increase if we included other environmental impacts in the bio-economic model, and thereby the difference between EVs would get larger. Nguyen *et al*. (2012), for example, estimated the environmental cost of pork using the monetising factors of the Stepwise2006 life cycle impact assessment method (Weidema, 2009) for a typical EU pork production. The following impact categories were included: global warming potential, acidification, eutrophication, nature occupation, ozone layer depletion, ionizing radiation, mineral extraction, ecotoxicity, human toxicity, respiratory in/organics and photochemical ozone-vegetation. They found that the environmental cost of producing pork was 1.9 EUR per kg, which was larger than the private cost of 1.4 EUR. Therefore, an increase in environmental costs (via including all kinds of impact categories and/or by raising shadow prices) increases the gap between EVs with and without including environmental costs.

4.5 Conclusions

This study assessed the effects of incorporating environmental costs and risk preferences of producers on economic values of pig breeding goal traits. A mean-variance utility function was used to derive the economic values at finishing pig level for Brazilian farrow-to-finish production system, assuming a typical farm with 1,500 sows. The results show that risk aversion of producers reduces the economic weights of sow efficiency traits (17%) while increasing the importance of production traits (7%) for the Brazilian farrow-to-finish production system. Similarly, the inclusion of environmental cost reduces the economic importance of sow efficiency traits (3%) while increasing the importance of production traits (1%) for a risk neutral producer. Environmental impacts such as emission of greenhouse gases (5%), and excretions of nitrogen (6%) and phosphorous (5%) per finished pig can be reduced via genetic change of the breeding goal traits while improving profitability. The results show that environmental costs and farmers' risk preferences matter when deriving economic values for a broad breeding goal aiming to improve both the economic and environmental sustainability of production systems.

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Conflict of interest statement

The authors do not have any conflict of interest to declare.

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Appendix 4A Production and economic results before genetic change

Table 4.A1 Key production and economic results for a typical Brazilian farrow-to-finish pig farm before genetic change (adopted from Ali *et al*., 2017a)

Parameters	Value	Standard deviation†
Key production variables		
Number of piglets weaned per year	35,199	0
Number of finished pigs per year	33,460	0
Feed conversion ratio (kg feed/kg gain) ††	2.66	0.45
Feed consumption of fattening pigs (t/year)	9,129	880
Age of finishing pig at slaughter (days)	168	0
Slaughter weight of finished pigs (kg/pig)	115.5	13.72
Environmental impact results		
Net GHG emission (t CO_2-eq/year) ‡	7,360	603
Excretion of volatile solids (t/year)	784	66
Excretion of N (t/year)	135	16
Excretion of P (t/year)	29	3
Economic results (×1000 US$/year)		
Replacement gilt and sow variable costs	688	23
Fattening pigs feed cost	1,819	219
Fattening pigs other variable costs	205	0
Fixed cost	305	0
Total costs	3,017	234
Returns from culled gilts and sows	72	6
Returns from finished pigs	3,504	539
Total revenues	3,576	539
Environmental cost of feed and net return from manure (×1000 US$/year)		
Environmental cost of feed	263	22
Net return from manure §	64	9
Profits (×1000 US$/year)		
Private profit	559	468
Social profit ¶	360	460

GHG, greenhouse gases.

† Standard deviations are zero for some of the variables as the stochasticity of only prices of feed and finished pigs, and pig growth model parameters are considered in the bio-economic model.

†† During the growing-finishing stage and including average feed consumption by lost pigs due to mortality.

‡ Total GHGs emission from feed production and manure management less avoided GHGs emission due to avoided artificial fertilizer production due to the use of manure as an organic fertiliser.

§ Fertiliser value of manure plus avoided environmental cost due to avoided artificial fertiliser production minus environmental cost of manure.

¶ Private profit minus environmental cost of feed plus net return from manure.

Chapter 5

Response to a selection index including environmental costs and risk preferences of producers

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Abstract

Genetic improvement of animals plays an important role in improving the economic and environmental sustainability of livestock production systems. This paper proposes a method to incorporate mitigation of environmental impacts and risk preferences of producers into a breeding objective via economic values (EVs). The paper assesses the effects of using these alternative EVs of breeding goal traits on discounted economic response to selection and on environmental impacts at commercial farm level. The application focuses on a Brazilian pig production system. Separate dam- and sire-line breeding programs that supply parents in a three-tier production system for producing crossbreds (fattening pigs) at commercial level were assumed. Using EVs that are derived from utility functions by incorporating risk aversion increases the cumulative discounted economic response to selection in sire-line selection (6%) while reducing response in dam-line selection (12%) compared to the use of traditional EVs. The use of EVs that include environmental costs increases the cumulative discounted social response to selection in both dam-line (5%) and sire-line (10%) selections. Emission of greenhouse gases, and excretion of nitrogen and phosphorus can be reduced more with genetic improvements of production traits than reproduction traits for the typical Brazilian farrow-to-finish pig farm. Reductions in environmental impacts do not, however, depend on the use of the different EVs (i.e. with and without taking into account environmental costs and risk). Both environmental costs and risk preferences of producers need to be considered in sire-line selection, and only environmental costs in dam-line selection to improve, at the same time, the economic and environmental sustainability of the Brazilian pig production system.

Keywords: Economic value, environmental impact, pigs, risk aversion, selection index

5.1 Introduction

Livestock production currently occupies 30% of ice-free terrestrial land (Steinfeld *et al*., 2006) and uses one-third of global cereal production to feed animals (Cassidy *et al*., 2013). It causes major environmental impacts through its dependence on scare resources (e.g., cropland, fossil fuel and water), and emission of pollutants to air, water and soil. Besides technological advancements in nutrition and management practices, genetic improvement of animals also plays an important role in reducing the environmental impacts of livestock production systems (Wall *et al*., 2010; Bell *et al*., 2013; Van Middelaar *et al*., 2014). Groen *et al*. (1997) noted that the genetic merit of animals should be improved through selection to fulfil the economic, ecological and social requirements of future livestock production systems (e.g., ensuring the growing demand for animal protein while minimizing environmental impacts). In multi-trait economic selection indices, economic values (EVs) guide the direction and emphasis of selection in the overall breeding objective by providing a measure of the relative importance of each trait (Hazel, 1943). A breeding objective describes the traits that the breeder aims to improve through selection. Pig breeding programs have been focusing on the genetic improvement of economically important traits such as litter size, growth rate, feed efficiency and lean meat with little attention to traits with noneconomic or little economic importance (e.g. environmental sustainability) (Olesen *et al*, 2000; Kanis *et al*., 2005). However, there is a growing public concern about the undesirable side effects of production systems (e.g. environmental impacts) and breeders need to include these in their breeding objectives on top of economic performance. Mitigation of environmental impacts in breeding objectives on the basis of correlated traits can be achieved by the use of EVs that incorporate environmental costs (Wall *et al*., 2010; Ali *et al*., 2018a). As Kanis *et al*. (2005) noted, more selection emphasis should be given to efficiency traits (e.g. feed efficiency) as these traits have environmental (and societal) values that are not represented when selection is based solely on economic aspects.

Current breeding programs define their breeding objectives with risk neutral producers in mind. These traditional breeding objectives are defined based on EVs derived from profit equations or bio-economic models that do not account for risk and the risk preferences of producers (i.e., they implicitly assume that producers are risk neutral). However, previous studies provide abundant evidence that agricultural producers are risk averse (e.g. refer to Moschini & Hennessy (2001) for an overview). Accordingly, models that do take risk into consideration, provide better predictive power of producers' behaviour than those that do not. Therefore, risk needs to be incorporated when deriving EVs since farmers' decisions (e.g. on the adoption of new genetics) and thereby farm profitability depend on their risk preferences. Ali *et al*. (2018a) proposed a method for integrating environmental costs and risk preferences of producers into the derivation of EVs of traits using a mean-variance utility function. They derived EVs for sow efficiency and production traits by including environmental costs and risk preferences of farmers for a pig production system. Responses to selection (i.e. genetic gains, economic returns and environmental impact reductions) depend on the values of the EVs used to define breeding objectives.

The use of incorrect EVs reduces efficiency of selection (e.g. Smith, 1983) and may even result in selection in the wrong direction (Cottle and Coffey, 2013). Cottle and Coffey (2013), for example, reported that a 10% underestimation of the relative EV of protein for UK Holstein cows would result in a loss of financial genetic gain of £0.17/cow/year. Although the figure looks very small, given the fact that genetic improvement produces permanent and cumulative change in performance, the accrued financial loss becomes substantial if it is computed for UK Holstein cow population over a given investment period (e.g. 20 years). Vandepitte and Hazel (1977) also reported that large errors (>50%) in the EV of feed efficiency of pigs can lead to a 76% loss in the relative efficiency of a selection index. To the best of our knowledge, no study to date has focused on the impact of the inclusion of risk preferences and environmental costs simultaneously when deriving EVs on the efficiency of selection.

In light of the foregoing discussion, the objective of this study was, therefore, to assess the effect of using EVs of pig breeding goal traits that account for environmental costs and risk preferences of producers on response to selection. Genetic gains of breeding goal traits, cumulative discounted economic returns and environmental impact reductions were predicted by following the gene flow method (McClintock and Cunningham, 1974; Brascamp, 1978). The effects are illustrated by applying it to a Brazilian pig production system. The results of the study are useful for breeding companies that need to update their breeding objectives to meet the growing demand for sustainable products and to properly acknowledge their customers' (i.e. risk averse producers) risk preferences.

5.2 Materials and methods

The first subsection introduces the multi-trait selection index method that is used to define the breeding objective. It also presents the method used to calculate correlations among different breeding objectives. This is followed by the presentation of the gene flow method, which is used to calculate the flow of genetic superiorities from nucleus to commercial herds in a three-tier production system. Finally, the multi-trait selection index method for the Brazilian pig production system is applied to assess the effect of using EVs that account for environmental costs and risk aversion on selection response.

5.2.1 Selection index theory

In this study, the multi-trait selection index method (Hazel, 1943) is used to define the breeding objective. The breeding objective is defined as the sum of the product of the additive genetic values of traits and the respective EVs. The breeding objective with m traits, also known as aggregate genotype, H, can be written as:

$$H = \sum_{i=1}^{m} EV_i g_i \tag{5.1}$$

where g_i is the additive genetic value of trait i (expressed as a deviation from the population mean) and EV_i is the economic value of trait i ($i = 1, \ldots, m$). In practice, the additive genetic values of traits are not known. However, each individual animals performance (i.e. phenotype performance) can be recorded for various traits. Then, the observations can be combined into a selection index, also known as selection criteria, I, which can be expressed as:

$$I = \sum_{j=1}^{n} b_j x_j \tag{5.2}$$

where x_j is the j^{th} phenotypic observation (in terms of deviations from the population mean) and b_j is the index weight or coefficient of observation j ($j = 1, \ldots, n$).

The selection index is the method of evaluating each animal, relative to the breeding objective, for selecting parents. It is developed to maximize the breeding objective, as constrained by the cost and ability to collect data on selection candidates and their relatives. The selection index can comprise the same or different traits as in the breeding objective (Schneeberger *et al*., 1992). Given the breeding objective H and selection index I, the problem is then to estimate the index weights b_j such that selection of an animal based on I maximizes response in H. The optimal index coefficients b_j, that minimize the variance of prediction errors, are estimated as:

$$b = P^{-1}\, C_{IH} EV \tag{5.3}$$

where P is an $n \times n$ phenotypic (co)variance matrix among the *n* selection index traits, C_{IH} is an $n \times m$ genetic (co)variance matrix among the *n* selection index traits and *m* breeding objective traits, and EV is an $m \times 1$ vector of EVs of traits in the breeding objective.

The variances of the breeding objective and selection index, and the co-variance between the two are estimated as:

$$\sigma_I^2 = b' P b \tag{5.4a}$$

$$\sigma_H^2 = EV' C_H EV \tag{5.4b}$$

$$\sigma_{HI} = b'C_{IH}EV \tag{5.4c}$$

where σ_I^2, σ_H^2 and σ_{HI} are the variance of the index, the variance of the breeding objective and the co-variance between the index and breeding objective, respectively; C_H is an $m \times m$ genetic variance-covariance matrix among the *m* breeding objective traits and the rest as defined above.

The accuracy of selection (r_{IH}) can be defined as (Van Vleck, 1993):

$$r_{IH} = \frac{\sigma_{HI}}{\sigma_I \sigma_H} = \frac{b'C_{IH}EV}{\sqrt{(b'Pb)(EV'C_H EV)}} \tag{5.5}$$

The rate of genetic improvement (response to selection) with respect to the breeding objective (and the underlying traits) depends on the amount of genetic variability in the population, the accuracy of the selection criteria, the intensity of selection, and the generation interval. Response to selection for the traits in the breeding objective in traits units is given by:

$$R_H = \frac{ib'C_{IH}}{\sqrt{b'Pb}} \tag{5.6}$$

where R_H is the selection response expressed in trait units, i is intensity of selection and the rest as defined above.

Due to low accuracy and bias of the estimates (Bourdon, 1998), the original index method was refined by subsequent studies to allow for using breeding values estimated by the best linear unbiased prediction (BLUP) technique (Henderson, 1963), and to allow for the inclusion of different traits in the breeding objective and selection index (Schneeberger *et al.*, 1992).

Breeding objectives may be correlated (e.g., objectives with and without considering environmental impacts). The correlation between two breeding objectives (say *i* and *j*) is given by (Vargas and Van Arendonk, 2004):

$$r_{ij} = \frac{EV_i' C_{ij} EV_j}{\sqrt{(EV_i' C_{ij} EV_i)(EV_j' C_{ij} EV_j)}} \tag{5.7}$$

where C_{ij} is the genetic variance-covariance matrix between traits in the two breeding objectives (*i* and *j*) and EV is the vector of EVs in the two breeding objectives.

5.2.2 The gene flow method

Pig production systems often consist of three production levels: nucleus, multiplier and commercial herds. The nucleus herd is used to select parents for the multiplier herd (and for the commercial herd). The multiplier herd supplies parents for the commercial herd where fattening pigs are finished for slaughter. Monetary gains over a given investment period from one round of selection of parents can be computed by using the gene flow method. The genetic superiority of selected animals of different lines in the nucleus needs to be transferred to the commercial level. Genetic superiority is transferred with different frequencies and involves time delays that depend on the production system and the crossbreeding scheme (Wolfova *et al.*, 2001). As McClintock and Cunningham (1974) outlined, the true weights of traits in multi-trait selection indices should be the products of the EVs of traits and their respective number of discounted expressions (i.e. expressions of genetic superiority discounted by a given interest rate within a defined investment period). The use of EVs that account for expressions of traits enables to select animals based on their discounted aggregate genetic values in monetary units. In the present study, the gene flow method outlined by McClintock and Cunningham (1974) was used to calculate the number of discounted expressions of traits. Since genetic improvements of some traits (e.g. growth rate) require shorter time period to be realized than some other traits (e.g. litter size), the number of discounted expressions are different among traits.

Monetary gains are defined as expressed genetic gains in the nucleus, multiplier and commercial levels following one round of selection. Suppose an age-class is a period of *k* years. Suppose m_t is a vector representing gene frequencies per sex in an age class in a particular season *t* (where a season is also *k* years). Then, it can be calculated as (Brascamp, 1978):

$$m_t = Rn_{t-1} + Pm_{t-1} \tag{5.8}$$

where *R* is a matrix defining gene transmission through reproduction, *P* is a matrix defining gene transmission through reproduction and aging, and

$$n_t = Qn_{t-1} \tag{5.9}$$

where *n* is a vector with gene frequencies per sex in the age classes, and *Q* is a matrix defining aging. Genetic superiorities of selected parents are used for m_0 and n_0. Then, the discounted cumulative genetic gains in monetary units (R_M) can be calculated as (Brascamp, 1978):

$$R_M = \sum_{t=1}^{T} m'(t)h\left(\frac{1}{1-r}\right)^t \tag{5.10}$$

where *m* is a vector with gene frequencies in defined age classes in all tiers by sex subclasses originating from the selected parents, *h* is an incidence vector describing the expression of a trait, which is equal to the product of the EV of the trait and the number of animals that expressed the trait in each sex-age class, and *r* is the discount rate.

5.2.3 Application to Brazilian pig production system

5.2.3.1 Definition of breeding objective and choice of selection index traits

Pig breeding programs include separate dam- and sire- lines. Dam-lines are mainly selected for reproduction traits (e.g. litter size) whereas sire-lines are selected for production traits (e.g. growth rate). However, dam-lines are also used to select for production traits. The traits number of piglets born alive per litter (NBA), pre-weaning mortality rate (PWM), weaning-oestrus interval (WOI) and average daily gain (ADG) are assumed to be in the dam-line breeding objective for the Brazilian production system. In the dam-line breeding objective, a desired-gain approach (see Kanis *et al*. (2005) for an overview) is followed for ADG in addition to obtaining maximum response in the reproduction traits. Following the desired gains approach, the genetic gain of ADG is set close to zero by changing the EV of ADG such that response in ADG will be close to zero. The traits ADG and feed conversion ratio (FCR) during the growing-finishing stage are assumed to be in the sire-line breeding objective (Ali *et al*., 2018a). The dam-line (H_1) and sire-line (H_2) breeding objectives are defined as:

$$H_1 = EV_{ADG} \times EBV_{ADG} + EV_{NBA} \times EBV_{NBA} + EV_{PWM} \times EBV_{PWM} + EV_{WOI} \times EBV_{WOI} \quad (5.11a)$$

$$H_2 = EV_{ADG} \times EBV_{ADG} + EV_{FCR} \times EBV_{FCR} \quad (5.11b)$$

where EV_i is the economic value of trait *i*; EBV_i is the BLUP estimated breeding value of trait *i*; and the rest as defined above. Breeding objectives, which account for environmental costs and risk preferences of producers, are defined by using the EVs that incorporate environmental costs and risk preferences of producers (Table 5.1). The first two cases (RN_NGHG and RN_GHG, Table 5.1) are for a risk neutral producer excluding and including greenhouse gases (GHGs) emission costs, respectively. The first case (RN_NGHG) refers to the traditional EVs, which are commonly used in breeding programs (and it is derived from a bio-economic model). Cumulative economic response to selection derived from EVs that incorporate GHGs emission costs imply social returns (i.e., economic return minus environmental cost). The third and fourth cases (RA_NGHG, RA_GHG; Table 5.1) are EVs that are derived from a mean-variance utility function by incorporating risk and risk aversion (Ali *et al*., 2018a). The fourth case (RA_GHG, Table 5.1) gives the EV that breeders should use for defining their breeding objectives as it accounts for emission of GHGs while serving risk averse producers.

In addition to the economically important traits (i.e. ADG, NBA, PWM and WOI) that are included in the breeding objective, the traits 21-day litter weight (21LW), piglet birth weight (PBW) and gestation length (GL) are included in the dam-line selection index. Breeders commonly use the trait 21LW for selection as it has favourable genetic correlations with other economically important traits. The trait PBW influences piglet survival and growth performance

(Beaulieu *et al*., 2010). Selection for litter size needs to be accompanied by selection for reducing PWM due to the negative genetic correlation between NBA and piglet survival (Lund *et al*., 2002). Rydhmer *et al*. (2008) reported that selection for longer GL increases piglet survival since the genetic correlation between GL and number of piglets that die after birth is negative. Moreover, the genetic correlations among GL, PBW and piglet growth rate are positive (Rydhmer *et al*., 2008).

Table 5.1 Economic values of breeding goal traits for Brazilian pig production system with and without considering environmental costs and risk preferences of producers (adapted from Ali *et al*., 2018a)

Traits [a]	RN_NGHG [b]	RN_GHG [b]	RA_NGHG [b]	RA_GHG [b]
Reproduction traits (US$ per sow per farrowing)				
ADG, g/day [c]	0.064	0.067	0.058	0.061
NBA, piglets per litter	20.854	21.806	17.243	18.378
PWM, %	-2.979	-3.131	-2.007	-2.208
WOI, days	-1.725	-1.826	-1.854	-1.991
Production traits (US$ per finished pig)				
ADG, g/day	0.065	0.070	0.069	0.073
FCR, kg/kg	-17.149	-19.022	-18.128	-19.941

[a] NBA, number of piglets born alive per litter; PWM, pre-weaning mortality rate of piglets; WOI, weaning-oestrus interval; ADG, average daily growth during the growing-finishing stage; FCR, feed conversion ratio during the growing-finishing stage (kg feed/kg gain).
[b] RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.
[c] Following a desired gain approach for ADG, the economic value of ADG is set to ensure that ADG is not deteriorating while selecting for reproduction traits (the actual economic value of ADG is large). It is set to make genetic gain of ADG close to zero for obtaining maximum possible genetic gains in the reproduction traits.

Although there is no carcass-quality-based payment system in Brazil, backfat thickness (BF) is included in the sire-line selection index as selection against BF increases lean meat and reduces feed cost (and environmental impacts). Residual feed intake (RFI) is also included in the index as this results in better response than including ratios such as FCR or feed efficiency (Gilbert *et al*., 2007; Cai *et al*., 2008). Saintilan *et al*. (2015) showed that in addition to the traditional feed efficiency traits (i.e., FCR or RFI), pig growth model parameters (i.e. mean protein deposition (PD), net energy intakes at 50 (FI50) and 100 kg body weights (FI100)) can also be included in the selection criteria since they have moderate to strong genetic correlations with respect to feed intake and feed efficiency. The use of these parameters in breeding programs might reduce the cost and difficulty of data recording for feed intake. Given the lack of accurate measures for feed intake throughout the life cycle of a pig, recording feed intake at 50 and 100 kg body weights might be a better alternative.

To reduce environmental impacts, the EVs that were derived by incorporating GHGs emission costs from feed production and manure (Table 5.1) were used in the breeding objective (and indirectly in the selection index as stated in Equation 5.3). For the dam- and sire-lines, the selection indices are defined as, respectively:

$$I_1 = b_{ADG} \times EBV_{ADG} + b_{NBA} \times EBV_{NBA} + b_{PWM} \times EBV_{PWM} + b_{WOI} \times EBV_{WOI} + b_{GL} \times EBV_{GL} + b_{PBW} \times EBV_{PBW} + b_{21LW} \times EBV_{21LW} \quad (5.12a)$$

$$I_2 = b_{ADG} \times EBV_{ADG} + b_{RFI} \times EBV_{RFI} + b_{PD} \times EBV_{PD} + b_{FI50} \times EBV_{FI50} + b_{FI100} \times EBV_{FI100} + b_{BF} \times EBV_{BF} \quad (5.12b)$$

where I_1 and I_2 are the selection indices for the dam- and sire- lines, respectively; b_i is index weight of trait *i*, EBV_i is the estimated breeding value of trait *i* and the rest as defined before.

The optimal index coefficients (b_i), that minimize the variance of prediction errors, are estimated using Equation 5.3. Phenotypic (co)variances are calculated from phenotypic correlations between traits and standard deviations (SDs). Genetic (co)variances are calculated from genetic SDs and genetic correlations between traits. The phenotypic and genetic SDs of the traits used to calculate the *P* and C_{IH} matrices are extracted from literature and are presented in Table 5.2. The heritability, and phenotypic and genetic correlations between traits are also extracted from literature and are presented in Table 5.3. Since separate dam- and sire- lines are assumed, the correlations between reproduction and production traits are zero. Since the Brazilian production system is also based on modern technologies such as high potential imported breeds and concentrated feed, the estimates used from the literature, which are mainly from European and North American production systems, are expected to hold. Here we assumed that there are no genotype by environment interactions (i.e. a given genotype is assumed to perform equally in Europe or in North America and in Brazil).

The deterministic simulation computer program SelAction (Rutten *et al.*, 2002) was used to estimate response to selection in trait units (genetic superiorities of selected parents) for the breeding goal traits, accounting for the reduction in variance due to selection and also corrects selection intensities for finite population sizes. The estimated genetic gains of breeding goal traits are used as genetic superiorities of selected parents (in nucleus herd) that can be transferred to the commercial level over a 10-year investment period in the gene flow method. The total discounted economic response per year in monetary units is estimated as described in the following subsection by using the gene flow method.

Table 5.2 Phenotypic (σ_p) and genetic (σ_g) standard deviations of traits

Traits	σ_p	σ_g	Source
Number of piglets born alive (NBA; piglets per litter)	2.85	0.90	Rydhmer (2000)
Pre-weaning mortality rate (PWM; %)	4.74	1.50	Rydhmer (2000)
Weaning-estrus interval (WOI; days)	3.16	1.00	Rydhmer (2000)
Gestation length(GL; days)	1.35	0.72	Hanenberg *et al*. (2001)
Piglet birth weight (PBW; g)	353.01	180.00	Miar *et al*. (2014)
21-day litter weight (21LW; kg)	16.01	5.31	Fundora (2015)
Average daily growth (ADG; g/day)	86.00	43.85	Saintilan *et al*. (2013)
Feed conversion ratio (FCR; kg/kg)	0.23	0.13	Saintilan *et al*. (2013)
Mean protein deposition (PD; g/day)	13.00	8.22	Saintilan *et al*. (2015)
Net energy intake at 50 kg body weight (FI50; MJ/day)	2.19	1.20	Saintilan *et al*. (2015)
Net energy intake at 100 kg body weight (FI100; MJ/day)	3.10	2.32	Saintilan *et al*. (2015)
Residual feed intake (RFI; g/day)	115.00	55.15	Saintilan *et al*. (2015)
Back fat thickness (BF; mm)	3.59	2.41	Saintilan *et al*. (2015)

5.2.3.2 Population structure, selection strategy and gene flow

In a three-tier production system, we assumed that the nucleus herd is used to select parents for the multiplier herd and fathers for the commercial herd. The multiplier herd supplies mothers for the commercial herd where fattening pigs are finished for slaughter. Assume there are two breeds/lines (A and B) in the nucleus herd to produce 1,500,000 crossbred pigs at commercial level per season, and assume a season is equal to six months. The structure of selection groups in the two-way crossing system (B×A) that follows from these assumptions is given in Table 5.4. Breed A, a dam-line, consists of 2,000 sows (half 12 and half 18 months old) and 50 boars (half 12 and half 18 months old) at the nucleus herd to produce replacements for the nucleus tier. Breed B, a sire-line, consists of 1,000 sows (half 12 and half 18 months old) and 40 boars (half 12 and half 18 months old) at the nucleus herd to produce replacements for the nucleus tier. In line A, each boar is mated to 40 sows and in line B with 25 sows, resulting in 10 offspring per female per farrowing (5 males and 5 females).

Table 5.3 Heritability (diagonal), genetic (above diagonal) and phenotypic (below diagonal) correlations between traits for dam-line (upper left corner) and sire-line (bottom right corner) selection

Traits	NBA	PWM	WOI	GL	PBW	21LW	ADG	FCR	PD	FI50	FI100	RFI	BF
NBA, piglets per litter	**0.10**[a]	0.34[b]	0.15[c]	-0.60[d]	-0.35[b]	0.07[b]	-0.20[c]						
PWM, %	0.04[b]	**0.10**[a]	0.31[f]	-0.37[g]	-0.24[g]	-0.69[b]	-0.24[g]						
WOI, days	0.10[c]	-0.01[f]	**0.10**[a]	0.00[h]	-0.05[e]	0.43[i]	0.10[c]						
GL, days	-0.12[d]	-0.14[g]	0.12[h]	**0.29**[h]	0.12[g]	0.03[j]	0.00[a]						
PBW, g	-0.32[b]	-0.28[g]	0.00[e]	0.15[g]	**0.26**[m]	0.87[b]	0.40[a]						
21LW, kg	0.36[b]	-0.70[b]	0.08[i]	0.16[j]	0.07[b]	**0.11**[b]	0.13[k]						
ADG, g/day	0.00[c]	0.04[g]	0.00[c]	0.00	0.42[a]	0.03[k]	**0.26**[p]	-0.33[p]	0.92[q]	0.52[q]	0.46[q]	0.11[p]	0.35[c]
FCR (kg/kg)							-0.41[p]	**0.32**[p]	-0.76[q]	0.35[q]	0.25[q]	0.58[p]	0.58[p]
PD, g/day							0.93[q]	-0.74[q]	**0.40**[q]	-0.04[q]	0.25[q]	-0.31[q]	−0.22[q]
FI50, MJ/day							0.39[q]	0.42[q]	0.07[q]	**0.30**[q]	0.30[q]	0.49[q]	0.74[q]
FI100, MJ/day							0.57[q]	0.16[q]	0.33[q]	0.19[q]	**0.56**[q]	0.45[q]	0.37[q]
RFI, g/day							0.00[p]	0.74[p]	-0.31[q]	0.61[q]	0.37[q]	**0.23**[p]	-0.04[p]
BF, mm							0.30[c]	0.33[p]	−0.13[q]	0.33[q]	0.25[q]	0.00[p]	**0.45**[c]

Refer to Table 5.2 for abbreviations of traits.
[a] Rydhmer (2000). [b] Huby *et al*. (2003). [c] Kanis et al. (2005). [d] Hermesch (2001). [e] Wallenbeck *et al*. (2016). [f] ten Napel *et al*. (1998). [g] Knol (2001). [h] Hanenberg *et al*. (2001). [i] Lundgren *et al*. (2014). [j] Using 14-day litter weight instead of 21-day litter weight (Hermesch, 2001). [k] Average of the first three parties (Tholen *et al*., 1996). [m] Miar *et al*. (2014). [p] Saintilan *et al.* (2013). [q] Saintilan *et al*. (2015).

Line A is used to produce replacement sows and sires for the nucleus and multiplier tiers, and sows for the commercial tier. In line A, the 24 months old sows and boars of the nucleus herd are replaced by selected candidates. Line B is used to produce replacement sows and sires for the nucleus herd and sires for the commercial tier. The crossbred pigs (fattening pigs) are the crosses of Sire B and Sow A (crosses of groups 17 and 18, Table 5.4). The replacements of commercial sires (Sire B) are produced by mating the 40 sires in nucleus herd (24 and 30 months old) with the 1000 sows (Sow B) in the nucleus herd (24 and 30 months old). The number of sires and sows in each tier together with their respective length of productive life is summarized in Table 5.5.

Table 5.4 Selection groups in a two way crossing system

Tier	Breed	Nucleus				Multiplier		Commercial	
		Sire A	Sow A	Sire B	Sow B	Sire A	Sow A	Sire B	Sow A
	Sire A	1	2						
Nucleus	Sow A	3	4						
	Sire B			5	6				
	Sow B			7	8				
Multiplier	Sire A	9	10						
	Sow A					11	12		
Commercial	Sire B			13	14				
	Sow A					15	16		
Fattening pigs								17	18

In line A, the female parents are selected in two stages. In stage 1, the female candidates are tested for ADG to select 6,000 candidates out of potential 10,000 candidates based on own performance and performance of 9 full sibs and 390 half sibs. In the second stage, the new generation of 1,000 females are selected out of 6,000 candidates based on own performance and performance of 2 full sibs and 117 half sibs on NBA, PWM, WOI, GL, PBW and 21LW. The 25 boar replacements are also selected in two stages. First, 800 boars are selected out of 10,000 males (2 males from offspring of 5 sows) based on own performance and performance of 390 half sibs on ADG. In the second stage, the 25 boars are selected out of the 800 selection candidates based on performance of 1 female full sib and 117 half sibs on NBA, PWM, WOI, GL, PBW and 21LW. For all traits, pedigree information (BLUP breeding values) are used. For line B, male selection candidates are tested for ADG, RFI, BF, PD, FI50 and FI100 whereas female selection candidates are tested for only ADG, BF and PD. The new generations of 20 boars are selected out of 5,000 candidates based on own performance and performances of 9 full sibs and 240 half sibs for ADG, BF and PD, and performances of 4 full sibs and 120 half sibs for RFI, FI50 and FI100. Similarly, the new generations of 500 gilts are selected out of 5,000 candidates based on own performance and performances of 9 full sibs and 240 half sibs for ADG, BF and PD, and performances of 5 full sibs and 120 half sibs for RFI, FI50 and FI100. For all traits, pedigree information (BLUP breeding values) are used.

Monetary gains over a 10-year investment period (20 seasons) from one round of selection of parents (selected before 6 months old) are computed by using the gene flow method. A 5% annual discount rate is assumed. For the assumed production structure presented above, the *P*, *Q* and *R* matrices that are used in the gene flow method can be found in Supplementary Material 5.S1.

Table 5.5 Productive seasons (1 season equals 6 months, first progeny born when sires or sows are 12 months old)

Tier	Breed	# Sires	# Sows	Productive life of sires (in seasons)	Productive life of sows (in seasons)
Nucleus	A	50	2,000	3 (the 24 months old 25 sires produce 25 boar replacements for multiplier)	3 (the 24 months old 1,000 sows produce 1,000 sow replacements for multiplier)
	B	40	1,000	4 (the 24 and 30 months old 40 sires produce 100 boar replacements for commercial)	4 (the 24 and 30 months old 1,000 sows produce 100 boar replacements for commercial)
Multiplier	A	75	5,000	3	5
Commercial	B×A	500	150,000	5	6

5.2.3.3 Environmental impacts at commercial farm level

Based on a bio-economic model for a typical Brazilian-farrow-to-finish commercial pig farm (Ali *et al*., 2018b), the effects of using the different EVs to select parents (Table 5.1) on commercial farm level emission of GHGs (kg CO_2-equivalent), nitrogen excretion (N, kg) and phosphorus excretion (P, kg) are assessed. As described in Ali *et al*. (2018b), the typical farm is assumed to own 1,500 sows and finishes about 33,500 fattening pigs per farm per year with a constant slaughter weight of 115.5 kg each. The number of sows and slaughter weights were assumed to be fixed. Reductions in emissions of GHGs, and excretions of N and P are calculated at commercial level for this typical pig farm that uses selected parents (based on the breeding structure described above in Subsection 5.2.3.2).

The derivation of these environmental impacts is as follow. First, using the bio-economic pig farm model (Ali *et al*., 2018b), the effects of a one unit genetic change of a trait (i.e. genetic superiorities of selected parents, Table 5.6) on emissions of GHGs, and excretions of N and P per finished pig for production and per sow for reproduction traits are derived. We refer to Ali *et al*. (2018a) for details regarding the effects of genetic changes of traits on environmental impacts for the Brazilian farrow-to-finish pig production system. Second, taking into account the time delay and transfer of genes from selections carried out in the nucleus herd in the current period, the cumulative reductions of environmental impacts at commercial farm level over a 10-year period are simulated using the gene flow method. Using the environmental impact reductions as EVs in the gene flow method (e.g. reduction in emission of GHGs in kg CO_2-eq due to a one unit genetic superiority of parents for a given trait), the environmental impact reductions over a 10-year investment period are derived for each trait.

5.3 Results

5.3.1 Genetic gains of breeding goal traits

Genetic superiority of selected parents from one round of selection, obtained from SelAction, for production and reproduction traits in line A, and for production traits in line B are summarized in Table 5.6 for the different breeding goal traits. Following the desired gain approach, genetic gains in ADG are kept close to zero in the dam-line breeding objective. As expected, selection on females results in higher genetic gains for reproduction traits than selection on males whereas selection on males results in higher genetic gains for production traits than selection on females. The optimal dam-line breeding objectives resulted in unfavourable effects for PWM and WOI. This implies that the economic return of selection for increased NBA outweighs the combined economic losses associated with increased PWM and WOI. As expected, accuracy of selection is higher for the sire-line breeding objective than for the dam-line breeding objective (among others due to higher heritability of production traits than reproduction traits).

Genetic gains of NBA are similar across the four cases implying that the inclusion of environmental costs and risk aversion does not affect response to selection for NBA (in trait units). Compared with the traditional breeding objective (RN_NGHG), genetic gains of PWM worsens (i.e. PWM increased) when derived from EVs that take into account risk aversion (12%; Table 5.6). For the sire-line breeding objective, the genetic superiority of selected parents decreases for ADG (by about 1%) with the inclusion of both environmental costs and risk aversion (RA_GHG) whereas it increases for FCR (by about 3%). The accuracy of selection has increased with the inclusion of environmental costs and risk aversion by about 1% for the dam-line whereas it remained the same for the sire-line breeding objectives.

Table 5.6 Simulated genetic superiorities of selected parents (in trait units) from one round of selection in separate dam-line and sire-line selections (using SelAction)

	RN_NGHG [a]		RN_GHG [a]		RA_NGHG [a]		RA_GHG [a]	
	Male	Female	Male	Female	Male	Female	Male	Female
Dam-line objective								
ADG, g/day [b]	1.106	2.352	1.102	2.353	1.105	2.325	1.103	2.333
NBA, piglets per litter	0.214	0.270	0.214	0.270	0.214	0.271	0.214	0.270
PWM, %	0.116	0.138	0.115	0.137	0.129	0.154	0.127	0.152
WOI, days	0.010	0.012	0.009	0.011	0.000	0.000	0.000	0.000
Variance of index	13.914	50.704	15.201	55.389	9.825	35.837	11.111	40.516
Variance of breeding goal	278.381	278.381	304.371	304.371	190.918	190.918	216.761	216.761
Accuracy of index	0.224	0.427	0.223	0.427	0.227	0.433	0.226	0.432
Sire-line objective								
ADG, g/day	24.836	15.889	24.627	15.765	24.865	15.906	24.590	15.744
FCR, kg/kg	-0.068	-0.032	-0.070	-0.033	-0.068	-0.032	-0.070	-0.033
Variance of index	3.759	3.332	4.492	3.967	4.217	3.741	4.912	4.335
Variance of breeding goal	13.898	13.898	16.497	16.497	15.612	15.612	18.015	18.015
Accuracy of index	0.520	0.490	0.522	0.490	0.520	0.489	0.522	0.491

Refer to Table 5.2 for abbreviations of traits.
[a] RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.
[b] Based on a desired genetic gain is set close to zero.

5.3.2 Cumulative discounted economic returns

The genetic superiority of selected parents of purebred lines A and B in nucleus herds is transferred to crossbred animals in the commercial level. For the Brazilian production system, the number of discounted expressions over 20 seasons from one round of selection are summarized in Appendix 5A, Table 5.A1. The discounted expressions are from 1 unit of genetic superiority, and assuming 1 unit of economic value and a 5% annual discount rate. As expected, in the dam-line selection, the number of expressions of production traits (ADG) is greater than the expressions of reproduction traits (e.g. NBA). Reproduction traits are expressed only on females whereas ADG is expressed on both sexes. Moreover, the timing of expression for production traits is shorter than reproduction traits, therefore, the cumulative number of discounted expressions for ADG is greater than the expressions for reproduction traits. The expressions of reproduction traits start after 3 seasons whereas it starts after 2 seasons for production traits in the nucleus tier. In the multiplier tier, expression of production traits from selections carried out in the dam-line starts after 4 seasons whereas it starts after 5 seasons for reproduction traits. The expressions of production traits from selection in the sire-line are zero as line B is not used in the multiplier tier. In the dam-line selection, the expression of genetic superiorities of production traits (ADG) starts after 6 seasons whereas it starts after 7 seasons for reproduction traits at commercial production level. In the sire-line selection, however, the expressions of genetic superiorities for production traits start after 4 seasons at commercial level.

The discounted economic returns are computed from the genetic superiorities of parents for each breeding goal trait (Table 5.6) by accounting for the number of discounted expressions (Appendix 5A, Table 5.A1). The discounted response to selection (in US$) are summarized in Table 5.7 for the four breeding objectives (RN_NGHG, RN_GHG, RA_NGHG and RA_GHG). The use of EVs that are derived by incorporating risk aversion (RA_NGHG; Table 5.7) increases the cumulative discounted economic return in sire-line selection (by about 6%) while reducing in dam-line selection (by about 12%) compared to the use of traditional EVs (RN_NGHG; Table 5.7). The use of EVs that are derived by incorporating environmental costs (RN_GHG; Table 5.7) increases the cumulative discounted social return in both dam-line (about 5%) and sire-line (about 10%) selections compared to response to selection based on the traditional EVs (RN_NGHG; Table 5.7). When environmental costs are included (RN_GHG and RA_GHG, Table 5.1), cumulative economic returns imply social returns (i.e., economic returns minus environmental costs). The EVs that include environmental cost are greater than the traditional EVs (Table 5.1). For example, in the sire-line, this resulted in greater genetic gain in FCR and lower genetic gain in ADG compared to the use of traditional EVs (Table 5.6). The aggregate social return in the sire-line (about US$ 7.2 million; Table 5.7) is greater when

EVs that include environmental costs are used than the purely economic return from traditional EVs (about US$ 6.6 million; Table 5.7) since an improvement in FCR reduces both feed cost and environmental costs associated with feed. Cumulative discounted social return decreased by about 7% for dam-line selection while it increased by 15% for sire-line selection when EVs that account both environmental costs and risk aversion (RA_GHG; Table 5.7) are used compared to discounted economic response to selection based on the traditional EVs (RN_NGHG; Table 5.7). For reproduction traits, RN_GHG case provides the highest cumulative discounted economic return (about US$ 1.2 million; Table 5.7). For production traits, RA_GHG case provides the highest cumulative discounted social return (about US$ 7.6 million; Table 5.7). The correlation between the traditional breeding objective (RN_NGHG) and the other breeding objectives that account for GHG emission costs and risk aversion is almost 1 (ranging between 0.998 for RA_NGHG in dam-line objective to 1.0 in RA_NGHG in sire-line breeding objective).

5.3.3 Environmental impacts at commercial farm level

The cumulative reductions in emissions of GHGs (kg CO_2-equivalent), and excretions of N and P (kg) at commercial farm level following from the use of selected parents are presented in Table 5.8 for sire-line and in Table 5.9 for dam-line selections. The results for the sire-line show that the expressions of genetic superiorities start after 4 seasons at commercial level (Table 5.8) whereas for the dam-line expressions of genetic superiorities start after 5 seasons for production traits and after 7 seasons for reproduction traits (Table 5.9). For the sire-line selection, on average, emission of GHGs decreases by 35,360 kg CO_2-equivalent per year (i.e. the cumulative reduction in the emission of GHGs is 353,601 kg over 20 seasons; Table 5.8) when EVs that are derived by accounting for both environmental costs and risk aversion are used. Reductions in environmental impacts following from genetic improvement of traits of the dam-line objective are negligible compared to the results of sire-line breeding objective. Reductions in environmental impacts (in both lines) do not depend on the use of the different EVs (i.e. with and without taking into account environmental costs and risk aversion). Compared with the traditional breeding objective (RN_NGHG), the use of EVs that account for both environmental costs and risk aversion resulted in about 1% additional reduction in emission of GHGs, and excretions of N and P. However, the inclusion of other environmental costs (e.g. acidification, eutrophication and GHGs emission from other stages of production) would further increase the differences among the different EVs (Table 5.1) and thereby these results might change.

Table 5.7 Discounted response to selection (US$) over 20 seasons from one round of selection in a dam-line for reproduction traits (line A) and a sire-line for production traits (line B) in a three tier production system for the different cases (1 season = 6 months)

Breeding objective	Season	ADG, g/day	NBA, per litter	PWM, %	WOI, day	Dam-line sub-total	ADG, g/day	FCR, kg/kg	Sire-line sub-total	Total
	1	0	0	0	0	0	0	0	0	0
	5	656	8,076	-601	-30	8,101	225,224	145,908	371,132	379,233
RN_NGHG [a]	10	12,529	41,292	-3,060	-154	50,607	265,848	172,226	438,074	488,681
	15	16,309	88,278	-6,613	-332	97,642	251,360	162,840	414,200	511,842
	20	17,640	102,230	-7,655	-384	111,831	235,032	152,262	387,294	499,125
	Cumulative	203,349	986,050	-73,667	-3,697	1,112,035	4,001,040	2,592,013	6,593,053	7,705,088
	1	0	0	0	0	0	0	0	0	0
	5	707	8,445	-626	-29	8,497	240,566	166,699	407,265	415,762
RN_GHG [a]	10	13,526	43,177	-3,191	-148	53,364	283,957	196,767	480,724	534,088
	15	17,602	92,308	-6,896	-319	102,695	268,482	186,044	454,526	557,221
	20	19,037	106,897	-7,983	-370	117,581	251,041	173,958	424,999	542,580
	Cumulative	219,488	1,031,064	-76,823	-3,561	1,170,168	4,273,580	2,961,364	7,234,944	8,405,112
	1	0	0	0	0	0	0	0	0	0
	5	686	6,695	-451	0	6,930	239,354	154,238	393,592	400,522
RA_NGHG [a]	10	13,105	34,238	-2,298	0	45,045	282,527	182,058	464,585	509,630
	15	17,068	73,146	-4,965	0	85,249	267,130	172,136	439,266	524,515
	20	18,467	84,709	-5,747	0	97,429	249,777	160,954	410,731	508,160
	Cumulative	212,799	817,169	-55,309	0	974,659	4,252,055	2,739,986	6,992,041	7,966,700
	1	0	0	0	0	0	0	0	0	0
	5	737	7,117	-489	0	7,365	250,516	174,753	425,269	432,634
RA_GHG [a]	10	14,073	36,390	-2,494	0	47,969	295,701	206,273	501,974	549,943
	15	18,324	77,796	-5,385	0	90,735	279,586	195,032	474,618	565,353
	20	19,823	90,092	-6,233	0	103,682	261,424	182,363	443,787	547,469
	Cumulative	228,469	868,976	-59,997	0	1,037,448	4,450,334	3,104,435	7,554,769	8,592,217

Refer to Table 5.2 for abbreviations of traits. [a] RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

Table 5.8 Cumulative reductions in environmental impacts (kg per season) at commercial farm level over 20 seasons from one round of selection in sire-line for a typical Brazilian farrow-to-finish pig farm for the different breeding objectives (1 season = 6 months)

Traits	Breeding objective	Environmental impact	1-3	4	5	10	15	20	Cumulative
	RN_NGHG [a]	GHG, kg CO_2-eq	0	-7,115	-7,115	-9,581	-10,247	-10,832	-152,802
		N, kg	0	-144	-144	-194	-208	-220	-3,101
		P, kg	0	-27	-27	-37	-39	-42	-588
	RN_GHG [a]	GHG, kg CO_2-eq	0	-7,328	-7,328	-9,868	-10,554	-11,157	-157,386
		N, kg	0	-149	-149	-200	-214	-226	-3,194
		P, kg	0	-28	-28	-38	-41	-43	-606
FCR	RA_NGHG [a]	GHG, kg CO_2-eq	0	-7,115	-7,115	-9,581	-10,247	-10,832	-152,802
		N, kg	0	-144	-144	-194	-208	-220	-3,101
		P, kg	0	-27	-27	-37	-39	-42	-588
	RA_GHG [a]	GHG, kg CO_2-eq	0	-7,328	-7,328	-9,868	-10,554	-11,157	-157,386
		N, kg	0	-149	-149	-200	-214	-226	-3,194
		P, kg	0	-28	-28	-38	-41	-43	-606
	RN_NGHG [a]	GHG, kg CO_2-eq	0	-9,349	-9,349	-12,591	-13,466	-14,234	-200,799
		N, kg	0	-217	-217	-292	-312	-330	-4,650
		P, kg	0	-39	-39	-53	-56	-60	-842
	RN_GHG [a]	GHG, kg CO_2-eq	0	-9,273	-9,273	-12,488	-13,355	-14,118	-199,158
		N, kg	0	-215	-215	-289	-309	-327	-4,612
		P, kg	0	-39	-39	-52	-56	-59	-835
ADG	RA_NGHG [a]	GHG, kg CO_2-eq	0	-9,360	-9,360	-12,605	-13,481	-14,250	-201,026
		N, kg	0	-217	-217	-292	-312	-330	-4,655
		P, kg	0	-39	-39	-53	-57	-60	-843
	RA_GHG [a]	GHG, kg CO_2-eq	0	-9,260	-9,260	-12,470	-13,336	-14,098	-198,872
		N, kg	0	-214	-214	-289	-309	-326	-4,605
		P, kg	0	-39	-39	-52	-56	-59	-834

Table 5.8 (**Continued**) Cumulative reductions in environmental impacts (kg per season) at commercial farm level over 20 seasons from one round of selection in sire-line for a typical Brazilian farrow-to-finish pig farm for the different breeding objectives (1 season = 6 months)

Traits	Breeding objective	Environmental impact	1-3	4	5	10	15	20	Cumulative
Sire-line subtotal	RN_NGHG [a]	GHG, kg CO_2-eq	0	-16,464	-16,464	-22,172	-23,713	-25,066	-353,601
		N, kg	0	-361	-361	-486	-520	-550	-7,751
		P, kg	0	-66	-66	-90	-95	-102	-1,430
	RN_GHG [a]	GHG, kg CO_2-eq	0	-16,601	-16,601	-22,356	-23,909	-25,275	-356,544
		N, kg	0	-364	-364	-489	-523	-553	-7,806
		P, kg	0	-67	-67	-90	-97	-102	-1,441
	RA_NGHG [a]	GHG, kg CO_2-eq	0	-16,475	-16,475	-22,186	-23,728	-25,082	-353,828
		N, kg	0	-361	-361	-486	-520	-550	-7,756
		P, kg	0	-66	-66	-90	-96	-102	-1,431
	RA_GHG [a]	GHG, kg CO_2-eq	0	-16,588	-16,588	-22,338	-23,890	-25,255	-356,258
		N, kg	0	-363	-363	-489	-523	-552	-7,799
		P, kg	0	-67	-67	-90	-97	-102	-1,440

GHG, greenhouse gases (kg CO_2-equivalent per farm per season); N, Nitrogen excretion (kg per farm per season); P, Phosphorus excretion (kg per farm per season).

Refer to Table 5.2 for abbreviations of traits.

[a] RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

Table 5.9 Cumulative reductions in environmental impacts at commercial farm level over 20 seasons (kg per season) from one round of selection carried out in dam-line for a typical Brazilian farrow-to-finish pig farm for the different breeding objectives (1 season = 6 months)

Traits	Breeding objective	Environmental impact	1-5	6	10	15	19	20	Cumulative
ADG	RN_NGHG [a]	GHG, kg CO_2-eq	0	-216	-546	-826	-988	-1,022	-9,863
		N, kg	0	-5	-13	-19	-23	-24	-228
		P, kg	0	-1	-2	-3	-4	-4	-41
	RN_GHG [a]	GHG, kg CO_2-eq	0	-216	-546	-826	-987	-1,021	-9,856
		N, kg	0	-5	-13	-19	-23	-24	-228
		P, kg	0	-1	-2	-3	-4	-4	-41
	RA_NGHG [a]	GHG, kg CO_2-eq	0	-214	-541	-819	-980	-1,014	-9,779
		N, kg	0	-5	-13	-19	-23	-23	-226
		P, kg	0	-1	-2	-3	-4	-4	-41
	RA_GHG [a]	GHG, kg CO_2-eq	0	-214	-542	-821	-981	-1,015	-9,798
		N, kg	0	-5	-13	-19	-23	-24	-227
		P, kg	0	-1	-2	-3	-4	-4	-41
NBA	RN_NGHG [a]	GHG, kg CO_2-eq	0	0	-560	-1,556	-1,992	-2,089	-16,647
		N, kg	0	0	-3	-9	-12	-12	-98
		P, kg	0	0	-3	-9	-11	-12	-92
	RN_GHG [a]	GHG, kg CO_2-eq	0	0	-560	-1,556	-1,992	-2,089	-16,647
		N, kg	0	0	-3	-9	-12	-12	-98
		P, kg	0	0	-3	-9	-11	-12	-92
	RA_NGHG [a]	GHG, kg CO_2-eq	0	0	-561	-1,559	-1,997	-2,093	-16,685
		N, kg	0	0	-3	-9	-12	-12	-98
		P, kg	0	0	-3	-9	-11	-12	-92
	RA_GHG [a]	GHG, kg CO_2-eq	0	0	-560	-1,556	-1,992	-2,089	-16,647
		N, kg	0	0	-3	-9	-12	-12	-98
		P, kg	0	0	-3	-9	-11	-12	-92

Table 5.9 (**Continued**) Cumulative reductions in environmental impacts at commercial farm level over 20 seasons (kg per season) ...

Traits	Breeding objective	Environmental impact	1-5	6	10	15	19	20	Cumulative
PWM + WOI	RN_NGHG [a]	GHG, kg CO_2-eq	0	0	+87	+246	+315	+330	+2,625
		N, kg	0	0	+1	+2	+3	+3	+28
		P, kg	0	0	0	+1	+2	+2	+14
	RN_GHG [a]	GHG, kg CO_2-eq	0	0	+87	+244	+312	+326	+2,597
		N, kg	0	0	+1	+2	+3	+3	+26
		P, kg	0	0	0	+1	+2	+2	+14
	RA_NGHG [a]	GHG, kg CO_2-eq	0	0	+94	+265	+339	+355	+2,825
		N, kg	0	0	+1	+3	+4	+4	+30
		P, kg	0	0	+1	+1	+2	+2	+15
	RA_GHG [a]	GHG, kg CO_2-eq	0	0	+93	+261	+334	+350	+2,785
		N, kg	0	0	+1	+3	+4	+4	+29
		P, kg	0	0	+1	+1	+2	+2	+15
Dam-line subtotal	RN_NGHG [a]	GHG, kg CO_2-eq	0	-216	-1,019	-2,136	-2,665	-2,781	-23,885
		N, kg	0	-5	-15	-26	-32	-33	-298
		P, kg	0	-1	-5	-11	-13	-14	-119
	RN_GHG [a]	GHG, kg CO_2-eq	0	-216	-1,019	-2,138	-2,667	-2,784	-23,906
		N, kg	0	-5	-15	-26	-32	-33	-299
		P, kg	0	-1	-5	-11	-13	-14	-119
	RA_NGHG [a]	GHG, kg CO_2-eq	0	-214	-1,008	-2,113	-2,638	-2,752	-23,639
		N, kg	0	-5	-15	-25	-31	-31	-294
		P, kg	0	-1	-4	-11	-13	-14	-118
	RA_GHG [a]	GHG, kg CO_2-eq	0	-214	-1,009	-2,116	-2,639	-2,754	-23,660
		N, kg	0	-5	-15	-25	-31	-32	-296
		P, kg	0	-1	-4	-11	-13	-14	-118

GHG, greenhouse gases (kg CO_2-equivalent per farm per season); N, Nitrogen excretion (kg per farm per season); P, Phosphorus excretion (kg per farm per season). Refer to Table 5.2 for abbreviations of traits. [a] RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

5.4 Discussion

In pig breeding programs, dam-lines are selected for reproduction (and production) traits whereas sire-lines are predominantly selected for production traits. In this study, a dam-line breeding objective with breeding goal traits ADG, NBA, PWM and WOI, and a sire-line breeding objective with traits ADG and FCR were assumed. We followed a desired-gain approach for ADG in the dam-line breeding objective (by changing the EV of ADG such that response to selection for ADG is close to zero). The use of the actual EV of ADG in the dam-line breeding objective would result in deterioration of all reproduction traits for the Brazilian production system. However, the main target of dam-line selection is to improve reproduction traits. Therefore, in the dam-line breeding objective, we aimed at achieving the maximum possible improvement in reproduction traits without deteriorating ADG.

Although the effect of the use of EVs that account for environmental costs and risk aversion of producers on genetic superiorities (in trait units) seems to be small, its effect on cumulative discounted economic response to selection is large as genetic improvement results in permanent and cumulative changes in performance. For example, the genetic superiorities (in trait unit) of NBA in the dam-line breeding objectives are the same when genetic superiorities are derived based on EVs that account and do not account for environmental costs and risk aversion (Table 5.6). However, cumulative discounted economic returns for NBA increased by about 5% and decreased by about 17% when derived from EVs that account for GHG emission costs and risk aversion, respectively (Table 5.7) following from the increase and decrease in EVs of NBA with GHG emission cost and risk aversion, respectively (Table 5.1). On the other hand, the genetic superiorities (in trait unit) of FCR in the sire-line breeding objectives increased by about 3%, 0% and 3% when they are derived based on EVs that account for environmental costs, risk aversion or both, respectively (Table 5.6). The associated increases in cumulative discounted economic responses to selections are about 14%, 6% and 20%, respectively (Table 5.7). The results of the present study are in line with the conclusion of Kanis *et al*. (2005) that mitigating environmental impacts requires more emphasis in selection given to efficiency traits (e.g. FCR) as these traits have environmental (and societal) values that are not captured by selection based solely on economic aspects.

The results of this paper showed that for reproduction traits, the use of EVs that incorporate environmental costs provides the highest cumulative discounted social return. For production traits, the use of EVs that incorporate both environmental costs and risk aversion provides the highest cumulative discounted social return. Therefore, breeding programs need to consider both environmental costs and risk preferences of producers in sire-line selection for improving both economic and environmental sustainability of Brazilian pig production system. On the other hand, breeding companies should consider only environmental costs for improving reproduction traits in dam-line selection. The results of the current study are useful for Brazilian pig integrators, which control the entire pork production chain including pig breeding, to improve the sustainability of their production systems and to meet the growing demand for sustainable pork. Since the use of EVs that incorporate GHGs emission costs improves both economic and environmental sustainability of pig production, policy makers may facilitate the design of a strong carbon market or may impose taxes on farms for emissions of GHGs or excretions of nutrients. Policy makers may also provide incentives (e.g., arrange finance at a lower interest rate) to encourage breeding companies to update their breeding objectives by incorporating environmental costs and risk aversion.

The largest contributors to environmental loads (e.g. emissions of GHGs, and excretions of N and P) in the pig production chain are feed production and manure management (Cherubini *et al*., 2015). Genetic improvement of efficiency traits contributes towards reductions of environmental impacts. As illustrated using a typical Brazilian farrow-to-finish commercial farm (Table 5.8), emissions of GHGs, and excretions of N and P can be reduced substantially with genetic improvements of production traits (in sire-line selection). Environmental impacts can further be reduced by about 1% by using EVs that are derived by incorporating GHG emission costs and risk aversion compared with the use of traditional EVs. Risk is an integral part of agricultural production (e.g. due to production variability and price volatility). Models that take into account risk preferences have a better predictive power of the behaviour of farmers (and hence farm profit which are the basis for deriving EVs) than those that do not (Moschini & Hennessy, 2001). The results of the present study also showed that selection indices (and thereby response to selections) are different with and without considering risk preferences.

The generation interval affects cumulative discounted economic return through genetic gains of traits and discounting. A lengthy generation interval delays the expressions of genetic superiorities at commercial production level thereby reducing the cumulative number of expressions within a given investment period (Brascamp, 1978). Furthermore, the present value of the monetary gains from the delayed expressions of genetic superiorities is lower because of the effect of time on the present value of money (via discounting). As the generation interval and discount rate used in this study are the same across the four breeding objectives (with and without accounting environmental cost and risk aversion), the comparisons of results are not affected between the objectives.

The discount rate also affects the cumulative discounted response to selection. In this study, a 5% annual discount rate is assumed. The 2017 annual interest rate for Brazilian 10-year government bond was about 7 percent[2]. A social discount rate needs to be used when animal breeding program investments should be considered as public projects (Smith, 1978). Bird and Mitchell (1980) suggested the use of social discount rates between 2% and 5% in breeding program investment appraisals. In the case of the present study, governments have leading roles to play in reducing environmental impacts of livestock production systems and in arranging technologies for risk-averse producers.

The cost of running the breeding programs is not considered in the present study. However, as the cost remains the same across the different breeding objectives, it does not undermine the comparisons of discounted returns among the different breeding objectives. For the assumed production system, the use of EVs that account for GHG emission costs and risk aversion results in a discounted return of more than US$ 887,130 over 10 years (compared to the traditional system that does not take into account GHG emission and risk).

The results of the present study are not directly comparable with other studies as the production systems, assumed breeding structures and breeding goals are different across studies. For a two-trait beef production system (ADG, kg/day and average daily dry matter intake (ADDMI; fractional change in kg/day)), Kulak *et al*. (2003) assessed the effect of using EVs that account for risk aversion on response to selection using a linear selection index based on own performance. Their results showed that genetic superiorities decreased from 0.079 to 0.077 for ADG and from 0.012 to 0.009 for ADDMI when EVs that account for risk aversion are used compared to the use of traditional EVs (for a fixed fattening period). In our study, response to selections in the sire-line (selection in males) marginally increased from 24.84 to 24.87 for ADG (g/day), and FCR (kg feed/kg gain) remained constant at -0.068 (for fixed output per farm per year) when risk aversion is considered. In Kulak *et al*. (2003), total economic response to selection (US$/animal) decreased from 20.68 to 5.68. In our study, total discounted cumulative economic response (US$/farm) increased from 6.59 million to 6.99 million in sire-line selection over 10 years. As described in Ali *et al*. (2018a), an improvement in ADG decreases duration of fattening and thereby feed consumption decreases (for a constant output). An improvement in FCR directly results in a reduction in feed consumption. Both these improvements result in a decrease in the variance of feed cost (due to the reduction in feed consumption while the variance of output is constant), which results in higher profit and utility. For Kulak *et al*. (2003), response to selection derived from EVs that account for risk aversion is lower compared to the traditional response to selection, as output is not fixed (they fixed fattening duration). Improvement in ADG and increase in ADDMI result in increased output. The increase in output results in increase in revenue but also increased variability of

[2] Based on bloomberg.com.

revenue (due to the variability of beef prices) and the increase in revenue is outweighed by the increase in the variability of profit. For Kulak *et al*. (2003), accuracy of selection decreased slightly from 54.1% to 53.8%, whereas in the present study accuracy of selection does not change with the use of EVs derived by accounting for risk aversion. The correlation between the two breeding objectives (using EVs with and without accounting for risk aversion) was 99.7% in Kulak *et al*. (2003), whereas it is 99.9% in the present study for the sire-line breeding objectives.

Van Middelaar *et al*. (2014) measured the effect of genetic improvements of milk yield and longevity for Dutch dairy production system on emissions of GHGs at chain level. For a labour income maximizing breeding objective, an improvement in milk yield and longevity by one genetic standard deviation unit resulted in a reduction of GHGs emission (CO_2-equivalent) of 247 and 210 kg per cow per year, respectively. When the breeding objective is to minimize emission of GHGs per kg of milk while maintaining labour income and milk production at least at the level before the genetic change in a trait, emission of GHGs can be reduced by 453 and 441 kg per cow per year for milk yield and longevity, respectively. Bell *et al*. (2013) reported that a one unit increase in survival and decreases in milk volume, live weight, dry matter intake, somatic cell count and calving interval in Australian dairy production system would increase net income while reducing emissions of GHGs per cow and per kg of milk produced.

5.5 Conclusions

This study assessed the effect of using EVs that account for GHGs emission costs and risk preferences of producers on response to selection in terms of genetic gains of breeding goal traits, cumulative discounted economic returns and cumulative reductions in environmental impacts. The approach was applied to a Brazilian pig production system. Compared to traditional EVs, the use of EVs that account for both GHGs emission cost and risk aversion results in a decrease in genetic superiority for ADG (1%), an increase for FCR (3%) whereas NBA is not affected. The use of EVs that take into account risk aversion increases the cumulative discounted economic return in sire-line selection (6%) while reducing in dam-line selection (12%) compared to the use of traditional EVs. On the other hand, the use of EVs that account for environmental costs increases the cumulative discounted social return in both dam-line (5%) and sire-line (10%). Emission of greenhouse gases, and excretion of nitrogen and phosphorus can be reduced more with genetic improvements of production traits than reproduction traits for the typical Brazilian farrow-to-finish pig farm. Reductions in environmental impacts do not, however, depend on the use of the different EVs (i.e. with and without taking into account GHGs emission costs and risk aversion). To improve both economic and environmental sustainability of the Brazilian pig production system, breeding companies need to consider both environmental costs and risk preferences of producers in sire-line selection. For dam-line selection, only environmental costs need to be considered.

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Appendix 5A Number of discounted expressions in a two-way crossing system for a three-tier production system

Table 5.A1 Number of (discounted) expressions[a] over 20 seasons from one round of selection in separate dam-line selection for production and reproduction traits, and sire-line selection for production traits in a three tier production system (1 season = 6 months)

Tiers	Traits		1	2	3	4	5	6	7	10	15	20	Cumulative
Nucleus	Production	ND	0	6,600	6,600	3,300	6,600	4,950	4,950	5,363	5,259	5,272	101,900
tier	traits_ dam-line	D	0	6,286	6,134	2,993	5,842	4,276	4,173	4,202	3,648	3,237	78,907
	Reproduction	ND	0	0	500	1,000	1,250	1,250	1,125	1,188	1,195	1,199	20,760
	traits_ dam-line	D	0	0	465	907	1,106	1,080	948	930	829	736	15,668
	Production	ND	0	4,740	4,740	2,370	4,740	3,555	3,555	3,851	3,777	3,786	73,183
	traits_ sire-line	D	0	4,514	4,405	2,150	4,196	3,071	2,997	3,018	2,620	2,325	56,669
Multiplier	Production	ND	0	0	0	12,100	0	7,260	7,260	7,986	9,105	9,460	138,056
tier	traits_ dam-line	D	0	0	0	10,975	0	6,271	6,120	6,257	6,315	5,807	102,193
	Reproduction	ND	0	0	0	0	500	500	833	1,275	1,755	1,911	23,354
	traits_ dam-line	D	0	0	0	0	443	432	703	999	1,217	1,173	16,750
	Production	ND	0	0	0	0	0	0	0	0	0	0	0
	traits_ sire-line	D	0	0	0	0	0	0	0	0	0	0	0
Commerc-	Production	ND	0	0	0	0	0	37,500	37,500	118,646	189,779	240,356	2,248,811
ial tier	traits_ dam-line	D	0	0	0	0	0	32,394	31,613	92,962	131,622	147,557	1,570,175
	Reproduction	ND	0	0	0	0	0	0	1,250	7,500	22,204	29,740	234,875
	traits_ dam-line	D	0	0	0	0	0	0	1,054	5,876	15,399	18,258	160,301
	Production	ND	0	0	0	187,500	187,500	112,500	225,000	252,500	270,047	285,465	4,026,949
	traits_ sire-line	D	0	0	0	170,068	165,969	97,182	189,679	197,840	187,292	175,251	2,966,263
Overall	Production	ND	0	6,600	6,600	15,400	6,600	49,710	49,710	131,994	204,143	255,087	2,488,768
	traits_ dam-line	D	0	6,286	6,134	13,968	5,842	42,941	41,906	103,421	141,584	156,602	1,751,274
	Reproduction	ND	0	0	500	1,000	1,750	1,750	3,208	9,963	25,154	32,850	278,989
	traits_ dam-line	D	0	0	465	907	1,549	1,512	2,705	7,806	17,446	20,167	192,720
	Production	ND	0	4,740	4,740	189,870	192,240	116,055	228,555	256,351	273,824	289,251	4,100,132
	traits_ sire-line	D	0	4,514	4,405	172,218	170,165	100,253	192,676	200,858	189,912	177,575	3,022,933

ND, non-discounted; D, discounted.

[a] From 1 unit of genetic superiority, and assuming 1 unit of economic value and 5% discount rate. Reproduction traits are expressed per sow per farrowing while production traits are expressed per fattening pig.

Supplementary Material 5.S1 The P, Q and R matrices used in the gene flow method in a three-tier production system

Table 5.S1 The *P* matrix

			Nucleus tier																		Multiplier tier										Commercial tier												
			Male A				Female A				Male B					Female B					Male A				Female A						Male B						Female A						
		Season	6	12	18	24	6	12	18	24	6	12	18	24	30	6	12	18	24	30	6	12	18	24	6	12	18	24	30	36	6	12	18	24	30	36	6	12	18	24	30	36	42
Nucleus tier	Male A	6	0	0.25	0.25	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0.25	0.25	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Male B	6	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female B	6	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Multiplier tier	Male A	6	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0.167	0.167	0.167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial tier	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0.125	0.125	0	0	0	0.125	0.125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.083	0.083	0.083	0.083	0.083	0.083
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
		42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Table 5.S2 The *Q* matrix

			Nucleus tier																	
			Male A				Female A				Male B					Female B				
		Season	6	12	18	24	6	12	18	24	6	12	18	24	30	6	12	18	24	30
Nucleus tier	Male A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Female B	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Multiplier tier	Male A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial tier	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

			Multiplier tier									
			Male A				Female A					
		Season	6	12	18	24	6	12	18	24	30	36
Nucleus tier	Male A	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
	Male B	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0
	Female B	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0
Multiplier tier	Male A	6	0	0	0	0	0	0	0	0	0	0
		12	1	0	0	0	0	0	0	0	0	0
		18	0	1	0	0	0	0	0	0	0	0
		24	0	0	1	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	1	0	0	0	0	0
		18	0	0	0	0	0	1	0	0	0	0
		24	0	0	0	0	0	0	1	0	0	0
		30	0	0	0	0	0	0	0	1	0	0
		36	0	0	0	0	0	0	0	0	1	0
Commercial tier	Male B	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0
		42	0	0	0	0	0	0	0	0	0	0

			Commercial tier												
			Male B						Female A						
		Season	6	12	18	24	30	36	6	12	18	24	30	36	42
Nucleus tier	Male A	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female B	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0
Multiplier tier	Male A	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial tier	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	1	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	1	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	1	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	1	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	1	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	1	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	1	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	1	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	1	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	1	0	0
		42	0	0	0	0	0	0	0	0	0	0	0	1	0

Table 5.S3 The *R* matrix

			Nucleus tier																		Multiplier tier										Commercial tier												
			Male A				Female A				Male B					Female B					Male A				Female A						Male B						Female A						
		Season	6	12	18	24	6	12	18	24	6	12	18	24	30	6	12	18	24	30	6	12	18	24	6	12	18	24	30	36	6	12	18	24	30	36	6	12	18	24	30	36	42
Nucleus tier	Male A	6	0	0.25	0.25	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0.25	0.25	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Male B	6	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female B	6	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0	0	0.25	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Multiplier tier	Male A	6	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0.167	0.167	0.167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial tier	Male B	6	0	0	0	0	0	0	0	0	0	0	0	0.125	0.125	0	0	0	0.125	0.125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.083	0.083	0.083	0.083	0.083	0.083
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Female A	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Chapter 6

The effect of genetic expenses on dynamic productivity growth

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Abstract

Genetic improvement of animals has been an important source of productivity growth in livestock farming. This paper used impulse response analysis to measure the effects of genetic expenses on input- and investment-specific dynamic productivity growths and their components. The application focused on panel data of Dutch specialized dairy farms over 2007-2013. Results show that productivity growth associated with breeding stock is negative (-1.2%), suggesting that the potential for doing investments in breeding stock has declined by 1.2% per year over the sample period for given levels of inputs and outputs. Technical changes associated with investments in capital and breeding stock are also negative. The results of the impulse response analysis show that higher expense on genetics leads to increase in productivity growth associated with inputs and investments in the first two years and then productivity starts to grow slowly.

Keywords: Dairy farming, data envelopment analysis, genetic improvement, impulse response analysis, input-specific dynamic productivity growth

6.1 Introduction

Genetic improvement of animals and plants has been an important source of productivity growth in agriculture, producing permanent and cumulative changes in performance. Genetic improvement can increase both the quantity and quality of output per unit of input (Atsbeha *et al*., 2012; Roibas and Alvarez, 2012; Babcock and Foster, 1991). According to Shook (2006), for example, large increases in milk yield (3,500 kg), fat (130 kg) and protein (100 kg) per cow per lactation have been achieved over the last 20 years from genetic, nutrition and management improvements; of which genetic improvement accounted for about 55%. To the best of our knowledge, only a few studies (e.g. Atsbeha *et al*., 2012; Roibas and Alvarez, 2012; Roibas and Alvarez, 2010; Steine *et al*., 2008), however, measured the contributions of genetic progress to farm productivity and profit.

Atsbeha *et al*. (2012) used the Malmquist productivity index to measure the productivity growth of Icelandic dairy production over the period 1997-2006, and decomposed it into genetic- and non-genetic-based technical changes, efficiency change and scale effects. An aggregate breeding index (average of sire merit indices used on all cows in the farm weighted by the number of active milking days of a cow) was used as a measure of genetic-based technology. The average annual productivity growth rate was 1.6%, of which genetic-based technical change accounted for 19%. A study by Roibas and Alvarez (2010) for Spanish commercial dairy farms showed that the gross margin has increased by up to 12% between 1999 and 2004 due to genetic progress. In a later study, Roibas and Alvarez (2012) analysed the role of genetics in improving milk composition by considering genetic indices (i.e. breeding values of protein and fat) as allocable inputs. They reported that a high genetic herd (i.e. a herd with higher breeding values relative to the population average breeding values) produces 742 kg of protein and 1,048 kg of fat more than the average genetic herd. Compared with the use of the average genetic herd, the use of a high genetic herd increases farm income by 6.6%. For the Norwegian red cattle production system, Steine *et al*. (2008) assessed the effect of genetic progress of ten breeding goal traits on farm profit. Seven of the traits had a positive and (statistically) significant effect on farm profit.

The main shortcoming of the above mentioned studies is the assumption that a herd with high genetic level in the current period improves farm productivity or profit in the same period. This assumption is likely inaccurate as the return from current period genetic levels of dairy cows or bulls, for example, usually requires several years before being realised; this is because the generation interval of cows is typically more than two years. Moreover, the effect of genetic progress on farm performance (e.g. milk production) is expressed over several years. Therefore, studying the effect of genetic progress on farm productivity changes requires a long term perspective. In this study, we use an impulse response function to assess the effect of improvements in genetic levels on dynamic productivity growth, estimated by the local projections method of Jordà (2005).

Yet another shortcoming of previous studies is that they did not account for the intertemporal linkages of production decisions. Investment in quasi-fixed inputs (e.g. buildings, milking robots and breeding stock) involves an intertemporal decision that affects current production while increasing future capital stock, which in turn affects future production. Investment in new breeding stock results in adjustment costs associated with, for example, removal of old stock, and new feeding and management practices. Like in other sectors (e.g. dairy manufacturing), the short-term impacts of technology adoption in dairy farming (e.g. deploying a milking robot) are expected to differ from their long-term impacts due to technology-specific learning. After adoption of a new technology, a period of adjustment exists (i.e. productivity under new technologies declines immediately after adoption) as producers are learning to adjust their production system to the new technology (e.g. Klenow, 1998; Jovanovic and Nyarko, 1996). For example, milk productivity may decline immediately after replacing a mature cow with a young heifer. However, the productivity of the heifer starts to increase from the first lactation to the second and to the third lactations.

Moreover, previous studies (e.g. Atsbeha *et al.*, 2012) measured overall productivity growth without linking productivity growth to the contributions of different inputs. Productivity growth associated with some inputs (e.g. feed) might be positive while being negative for some other inputs (e.g. energy). Disentangling the sources of productivity change, to explore which factors of production contribute to the change, is essential from a farm decision-making perspective (Kapelko *et al.*, 2017a). Identifying the factors of production (e.g. feed, capital, breeding stock) that are sources of inefficiency and productivity decline is crucial to improve farm performance.

In the light of the foregoing discussion the objectives of this study are twofold. Firstly, to measure the input- and investment-specific dynamic productivity changes (i.e. productivity growth, technical change, technical and scale inefficiency changes). Secondly, to investigate the impacts of (lagged) expense on genetics on dynamic productivity change (and its components) using an impulse response analysis. The empirical application focuses on panel data of Dutch specialized dairy farms over the period 2007-2013.

6.2 Materials and Methods

6.2.1 Dynamic Luenberger productivity growth indicator

Distance functions are commonly used for modelling multiple input-multiple output technologies. In this study, an input distance function is used to represent the Dutch dairy farm production technology, as during the sample period (2007-2013) the milk quota gave Dutch dairy farmers more autonomy to adjust inputs rather than outputs.

The input-specific dynamic Luenberger productivity indicator of Kapelko *et al*. (2017a) is employed to measure productivity and inefficiency changes associated with each variable input and investment in quasi-fixed inputs. It accounts for the adjustment costs associated with investment in quasi-fixed inputs (e.g. building and machineries). Suppose J farms ($j = 1, \dots, J$) produce M outputs $y = (y_1, \dots, y_M)$ by using N variable inputs $x = (x_1, \dots, x_N)$, H fixed inputs $L = (L_1, \dots, L_H)$, F quasi-fixed inputs $K = (K_1, \dots, K_F)$ and F gross investments corresponding to the quasi-fixed inputs $I = (I_1, \dots, I_F)$. Then, the dynamic production technology in time t that transforms x and I into y for a given level of L and K can be represented by an input requirement set (Serra *et al*., 2011) as:

$$P_t(y^t\colon K^t, L^t) = \{(x^t, I^t)\colon x^t, I^t\ can\ produce\ y^t, given\ K^t, L^t\} \tag{6.1}$$

where P_t is the production technology in time *t*. The following properties are assumed for the input requirement set (Silva and Stefanou, 2003): $P_t(y^t\colon K^t, L^t)$ is a closed and non-empty set, has a lower bound, is positive monotonic in variable inputs, is negative monotonic in gross investment, is a strictly convex set, output is freely disposable, and increases with capital stock and fixed inputs.

A dynamic directional input distance function ($\vec{D}$) can be used to represent the adjustment cost input requirement set:

$$\vec{D}^t(y^t, K^t, L^t, x^t, I^t; g_x^t, g_I^t) = \sup\left\{\sum_{n=1}^{N} \beta_n + \sum_{f=1}^{F} \gamma_f : \left(x_n^t - \beta_n g_{xn}^t, I_f^t + \gamma_f g_{If}^t, y_m^t, K_f^t, L_h^t\right) \in P_t\right\} \tag{6.2}$$

where g_x^t and g_I^t refer to directional vectors for scaling variable inputs and investment, respectively; β_n and γ_f refer to input n- and investment f-specific dynamic technical inefficiencies, respectively. The dynamic directional input distance function contracts variable inputs by $\beta_n \times g_x$ while expanding gross investments by $\gamma_f \times g_I$. The values of β_n and γ_f can be estimated using Data Envelopment Analysis (DEA). The estimation of Luenberger productivity growth requires solving four linear programming models under constant returns to scale (CRS): two single-period and two mixed-period models. The two single-period models measure the performance of farms in time *t* (and *t+1*) relative to the technology in time *t* (and *t+1*) (Equations 6.3 and 6.6). The mixed-period models measure the performance of farms in time *t* relative to the technology in time *t+1* (Equation 6.4), and the performance of farms in time *t+1* relative to the technology in time *t* (Equation 6.5). The four linear programming models to estimate the input- and investment-specific dynamic productivity growths are:

$$\vec{D}_i^t(y^t, K^t, L^t, x^t, I^t; g_x^t, g_I^t) = max_{\beta_n^1, \gamma_f^1, \lambda_j^1}\left(\sum_{n=1}^N \beta_n^1 + \sum_{f=1}^F \gamma_f^1\right) \quad (6.3)$$

Subject to

$$y_{mi}^t \leq \sum_{j=1}^J \lambda_j^1 y_{mj}^t, m = 1, \dots, M$$

$$\sum_{j=1}^J \lambda_j^1 x_{nj}^t \leq x_{ni}^t - \beta_n^1 g_{xn}^t, n = 1, \dots, N$$

$$\sum_{j=1}^J \lambda_j^1 L_{hj}^t \leq L_{hi}^t, h = 1, \dots, H$$

$$I_{fi}^t + \gamma_f^1 g_{If}^t - \delta_f K_{fi}^t \leq \sum_{j=1}^J \lambda_j^1 \left(I_{fj}^t - \delta_f K_{fj}^t\right), f = 1, \dots, F$$

$$\vec{D}_i^{t+1}(y^t, K^t, L^t, x^t, I^t; g_x^t, g_I^t) = max_{\beta_n^2, \gamma_f^2, \lambda_j^2}\left(\sum_{n=1}^N \beta_n^2 + \sum_{f=1}^F \gamma_f^2\right) \quad (6.4)$$

Subject to

$$y_{mi}^t \leq \sum_{j=1}^J \lambda_j^2 y_{mj}^{t+1}, m = 1, \dots, M$$

$$\sum_{j=1}^J \lambda_j^2 x_{nj}^{t+1} \leq x_{ni}^t - \beta_n^2 g_{xn}^t, n = 1, \dots, N$$

$$\sum_{j=1}^J \lambda_j^2 L_{hj}^{t+1} \leq L_{hi}^t, h = 1, \dots, H$$

$$I_{fi}^t + \gamma_f^2 g_{If}^t - \delta_f K_{fi}^t \leq \sum_{j=1}^J \lambda_j^2 \left(I_{fj}^{t+1} - \delta_f K_{fj}^{t+1}\right), f = 1, \dots, F$$

$$\vec{D}_i^t(y^{t+1}, K^{t+1}, L^{t+1}, x^{t+1}, I^{t+1}; g_x^{t+1}, g_I^{t+1}) = max_{\beta_n^3, \gamma_f^3, \lambda_j^3}\left(\sum_{n=1}^N \beta_n^3 + \sum_{f=1}^F \gamma_f^3\right) \quad (6.5)$$

Subject to

$$y_{mi}^{t+1} \leq \sum_{j=1}^J \lambda_j^3 y_{mj}^t, m = 1, \dots, M$$

$$\sum_{j=1}^J \lambda_j^3 x_{nj}^t \leq x_{ni}^{t+1} - \beta_n^3 g_{xn}^{t+1}, n = 1, \dots, N$$

$$\sum_{j=1}^J \lambda_j^3 L_{hj}^t \leq L_{hi}^{t+1}, h = 1, \dots, H$$

$$I_{fi}^{t+1} + \gamma_f^3 g_{If}^{t+1} - \delta_f K_{fi}^{t+1} \leq \sum_{j=1}^J \lambda_j^3 \left(I_{fj}^t - \delta_f K_{fj}^t\right), f = 1, \dots, F$$

$$\vec{D}_i^{t+1}(y^{t+1}, K^{t+1}, L^{t+1}, x^{t+1}, I^{t+1}; g_x^{t+1}, g_I^{t+1}) = max_{\beta_n^4, \gamma_f^4, \lambda_j^4}\left(\sum_{n=1}^N \beta_n^4 + \sum_{f=1}^F \gamma_f^4\right) \quad (6.6)$$

Subject to

$$y_{mi}^{t+1} \leq \sum_{j=1}^J \lambda_j^4 y_{mj}^{t+1}, m = 1, \dots, M$$

$$\sum_{j=1}^J \lambda_j^4 x_{nj}^{t+1} \leq x_{ni}^{t+1} - \beta_n^4 g_{xn}^{t+1}, n = 1, \dots, N$$

$$\sum_{j=1}^J \lambda_j^4 L_{hj}^{t+1} \leq L_{hi}^{t+1}, h = 1, \dots, H$$

$$I_{fi}^{t+1} + \gamma_f^4 g_{If}^{t+1} - \delta_f K_{fi}^{t+1} \leq \sum_{j=1}^J \lambda_j^4 \left(I_{fj}^{t+1} - \delta_f K_{fj}^{t+1}\right), f = 1, \dots, F$$

The parameter λ_j refers to peer weights (intensity vector) and δ_f refers to the depreciation rates of quasi-fixed inputs (e.g. capital and breeding stock). When computing dynamic technical inefficiency, the quasi-fixed input constraint in Equations 6.4 to 6.6, which is presented in terms of capital stock, gross investment and depreciation rate, is expressed in terms of net investment.

Given the input- and investment-specific dynamic technical inefficiencies under CRS, the Luenberger measure of input- and investment-specific dynamic productivity changes can be derived as (Oude Lansink *et al*., 2015; Kapelko *et al*., 2017a):

$$L_{xn} = \frac{1}{2} * (\beta_n^2 - \beta_n^4 + \beta_n^1 - \beta_n^3), n = 1, \dots, N \tag{6.7a}$$

$$L_{If} = \frac{1}{2} * \left(\gamma_f^2 - \gamma_f^4 + \gamma_f^1 - \gamma_f^3\right), f = 1, \dots, F \tag{6.7b}$$

where L_{xn} and L_{If} refer to the Luenberger measure of input *n*- and investment *f*-specific dynamic productivity changes, respectively.

The Luenberger measure of dynamic productivity change can be decomposed into technical change, technical inefficiency change under variable returns to scale (VRS) and scale inefficiency change as presented below. The measure L_{xn} can be decomposed into input-specific dynamic technical inefficiency change under CRS ($TEIC_{xn}^{CRS}$) and input-specific dynamic technical change (TC_{xn}):

$$TEIC_{xn}^{CRS} = \beta_n^1 - \beta_n^4, n = 1, \dots, N \tag{6.8a}$$

$$TC_{xn} = \frac{1}{2} * (\beta_n^4 - \beta_n^3 + \beta_n^2 - \beta_n^1), n = 1, \dots, N \tag{6.8b}$$

Dynamic technical inefficiency change measures the change in the position of a farm relative to the dynamic production frontier between two time periods, whereas dynamic technical change measures the shift of the frontier between two time periods. Similarly, the measure L_{If} can also be decomposed into investment-specific dynamic technical inefficiency change under CRS ($TEIC_{If}^{CRS}$) and investment-specific dynamic technical change (TC_{IF})

$$TEIC_{If}^{CRS} = \gamma_f^1 - \gamma_f^4, f = 1, \dots, F \tag{6.9a}$$

$$TC_{If} = \frac{1}{2} * \left(\gamma_f^4 - \gamma_f^3 + \gamma_f^2 - \gamma_f^1\right), f = 1, \dots, F \tag{6.9b}$$

The measures $TEIC_{xn}^{CRS}$ and $TEIC_{If}^{CRS}$ can be further decomposed into input- and investment-specific dynamic technical inefficiency changes under VRS and input- and investment-specific dynamic scale inefficiency changes, respectively. The input- and investment-specific dynamic technical inefficiency changes under VRS ($TEIC_{xn}^{VRS}$ and $TEIC_{If}^{VRS}$) are given by:

$$TEIC_{xn}^{VRS} = \beta_n^{1\,VRS} - \beta_n^{4\,VRS}, n = 1, \dots, N \tag{6.10a}$$

$$TEIC_{If}^{VRS} = \gamma_f^{1\,VRS} - \gamma_f^{4\,VRS}, f = 1, \dots, F \tag{6.10b}$$

The dynamic input- and investment-specific technical inefficiencies under VRS ($\beta_n^{1\,VRS}$, $\beta_n^{4\,VRS}$, $\gamma_f^{1\,VRS}$ and $\gamma_f^{1\,VRS}$) can be estimated by re-running Equation 6.3 and Equation 6.6 under VRS (by adding convexity restrictions $\sum_{j=1}^{J}\lambda_j^1 = 1$ in Equation 6.3 and $\sum_{j=1}^{J}\lambda_j^4 = 1$ in Equation 6.6).

The input- and investment-specific dynamic scale inefficiency changes (SIC_{xn} and SIC_{If}) are given by:

$$SIC_{xn} = (\beta_n^1 - \beta_n^4) - (\beta_n^{1\,VRS} - \beta_n^{4\,VRS}), n = 1, \dots, N \qquad (6.11a)$$

$$SIC_{If} = \left(\gamma_f^1 - \gamma_f^4\right) - \left(\gamma_f^{1\,VRS} - \gamma_f^{4\,VRS}\right), f = 1, \dots, F \qquad (6.11b)$$

6.2.2 Impulse responses by local projections

An impulse response analysis is used to track and measure the effect of genetic levels on the Luenberger dynamic productivity change indicator and its components. An impulse response function measures the responses of a system's variables to shocks. Jordà (2005) proposed the method of local projections for deriving impulse responses by overcoming the shortcomings of the traditional analytical impulse responses which were multi-period-ahead projections computed using autoregressive estimation techniques.

Consider the following autoregressive fixed effects panel data model of order r:

$$y_{it} = \alpha_i + \sum_{r=1}^{R}\beta_r y_{i,t-r} + \sum_{l=0}^{L}\gamma_l d_{i,t-l} + v_{it} \qquad (6.12)$$

where y_{it} is the dependent variable (e.g. productivity change) for farm i in year t; α_i is farm fixed effect for farm i; β and γ are parameters to be estimated; r denotes number of lags for y_t; l denotes the number of lags for d_t; d_t refers to a shock variable for a farm in year t and v_{it} is the error term that is independently and identically distributed: $v_{it} \sim \mathrm{N}(0, \sigma^2)$. Then the impulse response function of y_{it} to a shock d_t, k years after it starts can be stated as (Teulings and Zubanov, 2014; Jordà, 2005):

$$IRF(k) = E[y_{i,t+k} | d_{it} = d, y_{is}, d_{is}, s < t] - E\left(y_{i,t+k} | d_{it} = 0, y_{is}, d_{is}, s < t\right) \qquad (6.13)$$

where *IRF* is the impulse response function; *k* refers to prediction horizon; the conditional expectation $E[.|.]$ indicates the best, mean-squared error predictor and the rest as defined above.

Traditionally, impulse response functions (Equation 6.13) are estimated analytically for each prediction horizon k by solving the conditional expectation of $y_{i,t+k}$ as a function of the estimates of the parameters of Equation 6.12 (Teulings and Zubanov, 2014; Jordà, 2005). These estimation techniques are criticised for being sensitive to misspecification of the underlying model (Equation 6.12). The impulse responses become more sensitive to even slight specification errors when the model includes more lags of the dependent variable and the shock variable, and when the prediction horizon increases (Teulings and Zubanov, 2014; Jordà, 2005). They are also criticised for the complex methods of calculating standard errors as the standard errors are non-linear functions of estimated parameters. To overcome these problems, the local projection estimator of Jordà (2005) directly derives the coefficients of impulse responses for each time horizon based on sequential regressions of the dependent variable shifted several steps ahead (e.g. using simple ordinary least square estimator). Jordà (2005) demonstrated that impulse response estimates from local projections are consistent and inferences can be made using standard heteroscedastic and autocorrelation robust standard errors (e.g. as in Newy and West, 1987).

The estimates from local projection methods of Jordà (2005), however, suffer from a systematic bias which increases with the prediction horizon since the error term is correlated with current shocks (Teulings and Zubanov, 2014). Teulings and Zubanov (2014) proposed the inclusion of intermediate shocks in the model (i.e. shocks occurred between the current period *t* and the prediction period *t*+*k*) to obtain unbiased estimates of impulse response function for prediction horizon k. Several studies followed the (corrected) local projection technique for estimating impulse responses (e.g. Kapelko *et al*., 2017b; Kapelko *et al*., 2015; Bernal-Verdugo *et al*., 2013; Haug and Smith, 2012).

Following Teulings and Zubanov (2014), the corrected local projection estimator of Jordà (2005), for assessing the effect of expense on genetics on dynamic productivity changes and their components is given by:

$$y_{i,t+k} = \alpha_{ik} + \sum_{r=1}^{R} \beta_{rk} y_{i,t-r} + \sum_{l=0}^{L} \gamma_{lk} g_{i,t-l} + \sum_{l=0}^{k-1} \tau_l g_{i,t+k-l} + v_{i,tk}^{*} \tag{6.14}$$

where y_{it} is dynamic productivity change (and its components) for farm i $(i = 1,2, \dots, N)$ in year t $(t = 2, 3, \dots, T)$; k indicates the prediction horizon; α_{ik} is farm fixed effect for farm i; β, γ and τ are parameters to be estimated; r denotes number of lags for y_t; l denotes the number of lags for g_t; g_t refers to a dummy variable for genetic progress (1 genetic progress and 0 no genetic progress) for a farm in year t and $v_{i,tk}^{*} = \sum_{m=1}^{k-1} a_m u_{i,t+k-1-m} + u_{i,t+k-1}$ is the error term. Since the error term no longer contains current values of shocks, including the intermediate shocks in Equation 6.14 (the third summation) produces unbiased estimates of impulse response function for prediction horizon k (Teulings and Zubanov, 2014).

Ordinary least squares estimation of Equation 6.14 in levels results in inconsistent estimates since the lagged values of the dependent variable also depend on the time-invariant farm fixed effect α_i (Bond, 2002). Applying a within transformation to the data in order to estimate the model introduces another problem since the transformed lagged dependent variables are correlated with the transformed error term and thereby results in inconsistent estimates (Bond, 2002). This bias is also substantial in short panels. These problems can be solved by following different transformation and instrumental variable estimation procedures (e.g. using the second lagged value of the dependent variable as an instrument when estimating a transformed model) (Anderson and Hsiao, 1981).

Arellano and Bond (1991) pointed out that more lagged values can be used as instruments for 'later' years in the panel (i.e. for $T \geq 3$). They showed that a first-differenced Generalised Method of Moments (GMM) estimator for an autoregressive panel data model of order 1 provides asymptotically efficient estimates. If g_{it} is not strictly exogenous in Equation 6.14, lagged values of Δg_{it} can be used as instruments. Applying the original Arellano-Bond (1991) procedure by taking first-differences, removes α_i but also all time-invariant variables. In the present study, since g_{it} is a dummy variable, the Arellano-Bond estimator (1991) procedure is not applicable. However, Arellano and Bover (1995) extended the Arellano-Bond (1991) procedure by using differences of lagged dependent variable as instruments for endogenous time invariant variables. In the present study, Equation 6.14 is estimated using the Arellano and Bover (1995) two-step GMM estimator, also called the system GMM estimator. Heteroscedasticity and autocorrelation robust standard errors were estimated following Windmeijer (2005).

6.3 Empirical application

This study employs unbalanced panel data from 1,382 Dutch specialised dairy farms from 2007-2014, which were obtained from the accountancy firm FLYNTH (www.flynth.nl). Only specialised dairy farms, where (on average) at least 85% of total farm revenue is obtained from milk production, are considered. Farms that are observed for at least four consecutive years are included in the analysis as the impulse response analysis of productivity change requires at least four years to see the effect of lagged genetic progress. Two outputs (i.e. milk production and other output); two variable inputs (i.e. feed and other variable inputs), two quasi-fixed inputs (i.e. capital and breeding stock) and two fixed inputs (i.e. land and labour) are distinguished. Milk production is measured as fat and protein corrected *milk yield* in kg. This measurement accounts for the quality of milk in assessing the contribution of genetics; as genetic progress improves the quality of output in addition to yield. The second output is measured as *revenues* (in euro) from livestock and livestock products (excluding milk) and crop production. The variable inputs *feed* and *other variable inputs* are expressed in euros. Other variable inputs are expenses of energy, veterinary, seed, fertiliser and other crop related expenses. *Capital* is measured in euros as the book value of buildings and machinery.

Breeding stock is measured as the total value of breeding stock in euros. Net investments associated with quasi-fixed inputs are derived from capital stocks as $net\ investment_t = capital\ stock_{t+1} - capital\ stock_t$ (where *t* refers to years, 2007-2014). Following this formula, dynamic productivity change (and its components) are not estimated for the period 2013/14 as data on net investment is not available for the year 2014. The two fixed inputs are *land* in hectare and *labour* in annual working units (AWUs). Since a large share of labour (more than 95% in the sample farms) comes from family members, labour is considered as a fixed input. The directional vectors used in the estimation of the directional distance functions are the actual observed value of feed and other variable inputs x, and 20% of capital stock for investments for the quasi-fixed inputs K: $(g_x, g_I) = (x, 0.2 \times K_f)$, where f refers to *capital stock* and *breeding stock*.

All variables measured in monetary units are expressed in constant 2010 prices. Producer price indices (PPIs) from the EUROSTAT (2016) database are used to compute the implicit quantities as the ratio of value and PPI. For capital (buildings and machinery), a Törnqvist price index is used to compute the implicit quantity of capital. The final unbalanced panel dataset contains 8,586 observations from 1,382 farms (on average, a farm is observed for 6 consecutive years). Table 6.1 presents the descriptive statistics of the variables.

In this study, *expense on artificial insemination* (in euro per cow) is used as a measure of genetic progress. We assumed that a farm experiences genetic progress (i.e. a shock to the system) in year *t* if its expenditure on semen per cow (in constant 2010 prices) in that year is greater than the farm's median expenditure over the study period (2007-2013)[3]. It is used as a proxy for the genetic index of sires (total merit index of bulls): it is assumed to measure the genetic levels of sires used in a farm in a given year compared to the population average genetic level. We hypothesise that high expense on semen per dairy cow (compared to the median expenditure) has a positive effect on farm productivity growth as a result of the use of higher quality genetics. As a robustness check, we also used another measure of genetic progress, i.e. *investment spike on breeding stock* (refer to Appendix 6A for the details).

The impulse responses of input- and investment-specific dynamic productivity changes (and their components) to genetic progress during the period 2007-2013 are estimated for five prediction horizons ($k = 5$). Sequential regressions using the Arellano and Bover (1995) two-step GMM estimator with heteroskedasticity and autocorrelation robust standard errors (Windmeijer, 2005) are applied in STATA to estimate the impulse responses (Equation 6.14). The models are fitted using one lag for the dependent variables (i.e. dynamic productivity

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[3] The analogy is similar with the concept of investment spikes, which refer to abnormally high investment episodes relative to the typical investment rate of a firm (Kapelko *et al.*, 2015).

change and its components). Both the Akaike (AIC) and Bayesian information criterion (BIC) suggested that the models with one lag of the dependent variables (as explanatory variables) are the best specifications. The estimation of impulse response functions by the local projection technique of Jordà (2005) by itself guarantees robustness. The technique is more robust to misspecifications compared to the traditional analytical autoregressive models of estimating impulses (Jordà, 2005).

Table 6.1 Descriptive statistics of variables for Dutch specialised dairy farms over the period 2007-2014

Variables	Mean	Std. dev.	Minimum	Maximum
Quantities				
Protein and fat corrected milk (kg)	742,565	350,576	103,252	3,370,200
Other output (constant 2010 €) [a]	22,887	13,664	869	169,214
Feed (constant 2010 €) [a]	54,154	30,886	3,630	319,712
Other variable inputs (constant 2010 €) [a]	47,219	40,478	1,327	637,537
Land (ha)	47	21	9	206
Labour (AWU)	2	1	1	13
Capital (constant 2010 €) [a]	359,385	313,250	5,209	3,492,479
Breeding stock (constant 2010 €) [a]	83,199	41,576	5,600	450,755
Net investment in capital (constant 2010 €) [a]	23,294	131,441	-1,758,952	1,633,091
Net investment in breeding stock (constant 2010 €) [a]	4,035	11,940	-115,466	174,873
Prices				
Other output	1.081	0.101	0.898	1.202
Feed	1.192	0.152	0.997	1.378
Other variable inputs	1.055	0.046	0.989	1.097
Capital	0.987	0.011	0.972	1.000
Breeding stock	1.126	0.107	1.000	1.288
Expense on genetics	1.000	0.022	0.968	1.034

Notes: [a] Implicit quantities. N = 8,586.

6.4 Results and discussion

6.4.1 Decomposition of Luenberger dynamic productivity change

The results of the decomposition of the input- and investment-specific Luenberger dynamic productivity growth into technical change, technical inefficiency change and scale inefficiency change for Dutch dairy farms over the period 2007-2013 are presented in Tables 6.2 to 6.5.

Results of the estimation of productivity growth associated with feed input are presented in Table 6.2. Productivity associated with feed grew on average by 1.2% per year during the sample period (Table 6.2). The average Luenberger dynamic productivity growth rate of 1.2% for *feed* implies that the use of feed has reduced on average by 1.2% per year during the sample period while still producing the same level of output, holding other variable inputs and investments in capital and breeding stock constant. The productivity increase might be attributable to nutritional improvements and better feed management. On average, technical change accounted for about 64% of the productivity growth while technical inefficiency change accounted for about 31% of this growth. Over the sample period, the highest productivity growth associated with feed input (5.7%) was observed in 2009/10 mainly as a result of technical inefficiency change (4.3%) followed by technical change (1.6%). A 1.3% productivity decline (the lowest) was observed for feed input in 2011/12 mainly due to scale inefficiency change. The negative average scale inefficiency change associated with feed input (-0.06%) implies that productivity has slightly declined as a result of non-optimal scale of operation (i.e. operating either at a too small or too large scale).

Table 6.2 Decomposition of Luenberger dynamic productivity change associated with feed input for Dutch specialised dairy farms for consecutive years in the period from 2007 to 2013

	LPC [a]	TC [b]	TIC_VRS [c]	SIC [d]
2007/2008	0.0047	0.0104	-0.0058	0.0002
2008/2009	0.0044	0.0027	0.0049	-0.0032
2009/2010	0.0565	0.0157	0.0432	-0.0024
2010/2011	0.0240	-0.0018	0.0080	0.0179
2011/2012	-0.0127	0.0034	0.0001	-0.0162
2012/2013	-0.0033	0.0223	-0.0251	-0.0005
Average	0.0118 (0.067)	0.0084 (0.060)	0.0041 (0.093)	-0.0006 (0.054)

Notes: Standard deviations in parentheses. [a] Luenberger productivity change. [b] Technical change. [c] Technical inefficiency change under variable returns to scale. [d] Scale inefficiency change.

The average annual dynamic productivity growth for other variable inputs during the sample period was negative (about -3% per year; Table 6.3). Holding feed and investments in capital and breeding stock constant, this implies that the use of other variable inputs has increased on average by 3% per year during the sample period while still producing the same level of output. The productivity decrease might be due to the fact that modern productive breeds require more care to obtain the maximum output from a given cow (e.g. expenses on energy and veterinary services). The main source of productivity decline associated with other variable inputs was a decline in technical inefficiency change of about 1.3% per year, i.e. an increase in technical inefficiency. This means that the efficiency of Dutch dairy farms in utilising variable inputs such as veterinary services and energy has declined. Therefore, Dutch dairy farms may improve productivity associated with other variable inputs by designing a better heath and resource management system. Technical change and scale inefficiency change also contributed negatively to productivity growth of other variable inputs by about the same magnitude. Over the sample period, the highest productivity growth associated with other variable inputs (17.3%) was observed in 2011/12 mainly as a result of technical efficiency improvement. The negative average scale inefficiency change associated with other variable inputs (-0.73%) implies that productivity has declined due to a non-optimal scale of operation.

Table 6.3 Decomposition of Luenberger dynamic productivity change associated with other variable inputs for Dutch specialised dairy farms for consecutive years in the period from 2007 to 2013

	LPC [a]	TC [b]	TIC_VRS [c]	SIC [d]
2007/2008	0.0066	-0.0121	0.0265	-0.0079
2008/2009	-0.0058	0.0596	-0.0429	-0.0226
2009/2010	0.0488	-0.0103	0.0601	-0.0010
2010/2011	-0.2073	-0.0353	-0.1259	-0.0460
2011/2012	0.1730	-0.0169	0.1557	0.0342
2012/2013	-0.1385	-0.0209	-0.1175	-0.0001
Average	-0.0268 (0.213)	-0.0065 (0.118)	-0.0129 (0.230)	-0.0073 (0.130)

Notes: Standard deviations in parentheses. [a] Luenberger productivity change. [b] Technical change. [c] Technical inefficiency change under variable returns to scale. [d] Scale inefficiency change.

The average annual dynamic productivity change associated with investment in capital (building and machineries) during the sample period was 1.6 (Table 6.4). This implies that the potential for doing investments in capital has increased by about 32% of the capital stock per year ($= 1.6 \times 0.2 \times 100\%$) during the sample period while producing the same level of output, for a given levels of variable inputs and investment in breeding stock. This was mainly due to improvement in technical efficiency (1.96). For a given level of feed, other variable inputs and investment in breeding stock, the increase in the potential for doing investments due to technical inefficiency change ($39\% = 1.96 \times 0.2 \times 100\%$) implies that the potential for doing investments in capital has increased by about 39% of the capital stock per year following from improvements in the optimal use of available capital. Technical inefficiency decreased substantially during the sample period where the highest change was observed in 2007/08. Dutch specialised dairy farms experienced a technical regress of about 13% per year during the sample period ($-13\% = -0.64 \times 0.2 \times 100\%$). This implies that the frontier has been shifting downward over time. Although the efficiency of farmers increased in the use of technologies (e.g. machineries) over the sample period, they were not successful in adopting new technologies for bringing in technical progress. This might be due to higher costs to comply with environmental regulations such as manure disposal and emission reducing measures, which impose higher costs on dairy farms, but do not add directly to production. Over the sample period, productivity associated with investment in capital has increased (5.61%) as a result of improvement in scale of operation associated with capital (i.e. following from production technology movement from VRS towards CRS).

Table 6.4 Decomposition of Luenberger dynamic productivity change associated with investment in capital for Dutch specialised dairy farms for consecutive years in the period from 2007 to 2013

	LPC [a]	TC [b]	TIC_VRS [c]	SIC [d]
2007/2008	7.3689	-3.9091	11.2902	-0.0122
2008/2009	0.4561	0.2834	0.6208	-0.4480
2009/2010	9.7266	0.6023	7.2443	1.8800
2010/2011	-3.2455	-2.2400	-0.6376	-0.3679
2011/2012	0.0129	-0.1817	-0.3762	0.5708
2012/2013	0.0923	0.0739	-0.1008	0.1193
Average	1.6012 (8.258)	-0.6416 (8.701)	1.9623 (10.929)	0.2805 (2.501)

Notes: Standard deviations in parentheses. [a] Luenberger productivity change. [b] Technical change. [c] Technical inefficiency change under variable returns to scale. [d] Scale inefficiency change.

The average annual dynamic productivity change associated with investment in breeding stock during the sample period was negative (-0.06; Table 6.5). This suggests that the potential for doing investments in breeding stock has declined on average by about 1.2% per year during the sample period (as $g_I = 0.2 \times K$), for a given level of feed, other variable inputs and investment in capital. The main source of productivity decline associated with investment in breeding stock was technical regress (i.e. an average technical regress of about 2.2%). This might be due to the fact that investment in improved breeding stock need to be accompanied by an expansion of other inputs (e.g. feed, veterinary services, labour) and an investment in capital assets (e.g. a new milking robot) or expansion of output. The average technical inefficiency change is positive and the highest change was observed in 2012/13. This suggests that over the sample period, the efficiency of farms in utilising the available breeding stock has increased. Over the sample period, productivity associated with investment in breeding stock has increased (0.34%) as a result of improvement in the scale of operation associated with breeding stock (i.e. following from the shift/movement in the production technology from VRS to CRS).

From the decompositions of investment-specific dynamic productivity growths associated with investments in capital and breeding stock (Table 6.4 and Table 6.5), we observe that the average technical changes are negative for Dutch dairy farms over the period 2007-2013. This implies that, for producing the same level of output, the potential for doing investments in capital (e.g. milking robots) and breeding stocks to achieve technical progress has declined over the sample period for a given level of variable inputs. This might due to higher costs to comply with environmental regulations (e.g. manure disposal and emission reducing measures), which impose higher costs but do not add directly to production. Over the sample period, Dutch dairy farms rather improved their productivity associated with investments by a better utilisation of available capital and breeding stocks (i.e. by improving technical efficiency) and to some extent by improving scale of operation. Farmers might have also been discouraged to make investments in modern technologies and breeds as a result of the milk quota system that posed an upper limit on milk production during the sample period. Therefore, there is a potential to improve productivity growth of Dutch dairy farms via technical progress. Further research is required to study the causes behind lack of investments and to make business and policy recommendations accordingly.

Table 6.5 Decomposition of Luenberger dynamic productivity change associated with investment in breeding stock for Dutch specialised dairy farms for consecutive years in the period from 2007 to 2013

	LPC [a]	TC [b]	TIC_VRS [c]	SIC [d]
2007/2008	-0.5242	-0.6246	-0.0447	0.1451
2008/2009	0.8297	0.3260	0.4837	0.0200
2009/2010	0.2864	0.5794	-0.2978	0.0048
2010/2011	-0.9120	-0.2157	-0.6090	-0.0872
2011/2012	-0.4195	-0.4364	-0.0405	0.0574
2012/2013	0.2841	-0.4284	0.6739	0.0386
Average	-0.0618 (1.037)	-0.1114 (0.735)	0.0324 (1.156)	0.0172 (0.396)

Notes: Standard deviations in parentheses. [a] Luenberger productivity change. [b] Technical change. [c] Technical inefficiency change under variable returns to scale. [d] Scale inefficiency change.

6.4.2 Effect of genetic progress on dynamic productivity growth and its components

The results of the impulse response analysis for measuring the effect of genetic progress on input- and investment-specific dynamic productivity growth and its components are presented in Table 6.6. The statistically significant results in the first two years (Table 6.6) suggest that the effect of using purchased semen starts in the same year of application. For instance, if a cow is inseminated in the first week of January, the effect of that insemination starts to materialize on milk production of that cow after nine months (e.g. October). Productivity change associated with feed increases by 0.0074 and 0.0175 after one and two years after a farm spends more than the median expenditure on artificial insemination, respectively. Holding output, other variable inputs and investments constant, these results imply that spending more than the median expenditure leads to a decrease in the use of feed by 0.74% and 1.75% per year after one and two years from the time of spending, respectively. The second year effect is mainly attributed to the effect on scale inefficiency change. Spending greater than the median expenditure on artificial insemination improves technical efficiency associated with feed after three years.

One year after its expenditure, genetic progress following from spending more than the median on semen has a positive and statistically significant effect on productivity growth associated with other variable inputs. This effect is mainly attributable to technical inefficiency change and technical change. Farms that spend more than the median expenditure on artificial insemination experience an increase (0.0756) and a decrease (0.1103) in productivity growth associated with other variable inputs after one and two years from the time of spending, respectively. Holding output, feed and investments constant, these results imply that spending more than the median expenditure leads to a decrease and an increase in the use of other variable inputs by 7.56% and 11.03% per year after one and two years from the time of spending, respectively. Although spending more than the median expenditure has a negative effect after two years, it has a positive and statistically significant effect on productivity growth associated with other variable inputs after three and four years. This effect is mainly attributable to the technical inefficiency change.

One year after spending more than the median expenditure, productivity growth associated with investment in capital increases by 3.10. This implies that, holding output, feed and investment in breeding stock constant, spending more than the median expenditure leads to an increase in the potential for doing investments in capital after one year by 62% of the capital stock (as $g_I = 0.2 \times K$) per year. This effect is mainly attributed to the effect of spending on technical inefficiency change. One and four years after spending, productivity growth associated with investment in breeding stock increases by 0.76 and 0.58. These results imply that, holding output, feed and investment in capital constant, spending more than the median expenditure leads to an increase in the potential for doing investment in breeding stock by 15.2% and 11.6% of the breeding stock (as $g_I = 0.2 \times K$) per year after one and four years, respectively. These effects are mainly attributable to technical change and technical inefficiency change, respectively. However, it causes a decline in productivity growth after two and three years due to its negative and statistically significant effect on technical inefficiency change associated with investment in breeding stock.

Table 6.6 Impulse responses of input- and investment-specific Luenberger dynamic productivity changes and their components to expense on artificial insemination [a]

Years after expenditure (k)	LPC [b]	TC [c]	TIC [d]	SIC [e]
Feed				
1	0.0074***	0.0069***	0.0072**	-0.0059***
2	0.0175***	0.0017	0.0027	0.0072***
3	-0.0039	-0.0169***	0.0212***	0.0031
4	-0.0063	0.0143***	-0.0171	-0.0073**
5	0.0105	0.0067	-0.0012	0.0201
Other variable inputs				
1	0.0756***	0.0157***	0.0227***	0.0103**
2	-0.1103***	-0.0153***	-0.0743***	-0.0126***
3	0.0524***	-0.0070	0.1088***	0.0002
4	0.0970***	-0.0038	0.0225	0.0016
5	0.0028	0.0165	-0.0468	0.0257
Investment in capital				
1	3.0962***	0.9193***	1.8478***	0.5242***
2	0.0898	-0.7364**	0.0957	-0.1180
3	-3.0996***	-0.9258**	-1.1921**	0.0055
4	-0.0645	0.7905*	-1.0122	0.0884
5	0.9125	1.0086	0.3043	-0.3402
Investment in breeding stock				
1	0.7644***	0.3809***	0.1996***	0.0270*
2	-0.6706***	0.0604*	-0.5026***	-0.0358**
3	-0.7927***	-0.3337***	-0.4747***	-0.0296
4	0.5761***	-0.1271**	0.7076***	0.0285
5	0.2388	0.0382	0.0272	0.1763

*** Significant at 1%; ** Significant at 5%; * Significant at 10%.
[a] According to this measure, if a farm's expense on artificial insemination per cow in constant 2010 prices in a given year is greater than its median expenditure in 2007-2013, a farm is assumed to experience genetic progress in that year. [b] Luenberger productivity change. [c] Technical change. [d] Technical inefficiency change under variable returns to scale. [e] Scale inefficiency change.

The results of the impulse response analyses using the measure of investment spike on breeding stock are also similar to the results of expense on artificial insemination (Appendix

6A, Table 6A.1). The results of the impulse response analyses suggest that expense on genetics has the potential to improve productivity of dairy farms. Productivity growth associated with inputs and investments increases following from higher expense on genetics in the first two years and then productivity starts to grow slowly (with very few exceptions). The negative coefficients do not imply a reduction in productivity as a result of expense on genetics (Table 6.6). They rather imply that productivity growth declines, i.e. the productivity in time *t+1* is lower than the productivity in time *t*. The benefits of using a high quality semen in the first two years could be attributed to the increase in milk production and increase in revenues following from sales of (at least 50% of) the calves. The positive and statistically significant effect of expense on artificial insemination on productivity growths of investment in breeding stock and other variable inputs, four years from the time of spending, could be attributed to the effect of using replacement heifers that are raised within the farm, which received 50% of their genes from the high quality semen.

6.5 Conclusions

This study measured the input- and investment-specific Luenberger dynamic productivity growth indicators and their components for Dutch specialised dairy farms over the period 2007-2013. The average yearly input-specific productivity changes are 1.2% for feed, -2.7% for other variable inputs, 32% for investment in capital and -1.2% for investment in breeding stock. Technical change is the main component of productivity changes associated with feed (positively) and investment in breeding stock (negatively) whereas technical inefficiency change is the main component of productivity changes associated with other variable inputs (negatively) and investment in capital (positively). The negative productivity growth associated with breeding stock (-1.2%) suggests that, holding output, variable inputs and investment in capital constant, the potential for doing investments in breeding stock has declined by 1.2% per year over the sample period. Farmers might have been discouraged to make investments in modern breeds (and technologies) as a result of the milk quota system that limits milk production during the sample period. The negative technical changes for investments suggest that there is potential for Dutch dairy farms to increase productivity by raising technical progress (e.g. by doing productive investments on top of unproductive investments that are done to comply with environmental regulations such as manure disposal and emission reducing measures).

This study also measured the effect of genetic progress on input- and investment-specific dynamic productivity growth indicators and their components using an impulse response analysis. The results of the impulse response analyses show that expense on genetics has the potential to improve productivity of dairy farms. The results suggest that productivity growth associated with inputs and investments increases following from higher expense on genetics in the first two years after expense and then productivity starts to grow slowly (with very few exceptions). The benefits of using a high quality semen in the first two years could be attributed to the increases in milk production and revenues following from sales of (at least 50% of) the calves. Expense on genetics results in an increase in productivity growths associated with other variable inputs and investment in breeding stock after four years from spending. These increases could be attributed to the effect of using replacement heifers that are raised within the farm, which received 50% of their genes from the high quality semen.

The combination of input-specific dynamic productivity growth indicators with impulse response analysis is a promising method for measuring the contribution of (lagged) genetic levels to productivity growth associated with each variable input and investments. However, a good measure of genetic progress is required. This study used expense on artificial insemination as a proxy for genetic progress. This measure is imperfect as expenses on artificial insemination consist of two confounding components that cannot be distinguished in the dataset used in this study. First, a higher genetic expense per cow implies acquisition of higher quality semen that helps to enhance productivity. Second, (for the same or lower level of productivity) a higher expense might also be due to farm-level inefficiencies. Less fertile (unproductive) cows require several inseminations which raise semen expense (it might also be due to managerial inefficiency, for example, in detecting heat period). Since expense on artificial insemination is not corrected for managerial inefficiencies, its effect on productivity growth is understated in the present study. The negative effects of expense on artificial insemination on productivity and efficiency changes for some of the inputs and investments might also be due to the outweigh of expenditure following farm inefficiencies over expenditure on quality genetics. A cow with a longer calving interval produces less milk per year while it requires several inseminations. In this case the expense on genetics does not lead to an improved genetic level, but it is spent to solve problems that may have their cause in other sources of inefficiency.

Future research may use the total merit index of a herd as a measure of genetic levels at farm level. The total merit index (also known as aggregate genotype) is a linear function of economically important traits (Miesenberger and Fuerst, 2006). It is a weighted average of breeding goal traits (i.e. estimated breeding values of traits such as milk yield, fat and protein contents weighted by their respective economic values). Estimated breeding values of traits have already been employed in assessing the contribution of genetic levels to farm productivity and profit using static models, with the assumption that a high genetic herd in the current period results in higher productivity or profit in the same period (e.g. Atsbeha *et al.*, 2012; Roibas and

Alvarez, 2012; 2010; Steine *et al*., 2008). A dynamic approach is required to better capture the effect of genetic levels on farm performance.

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Appendix 6A

Investment spike on breeding stock is also used as a proxy for genetic progress of farms. In this study, a spike is defined as a year in which a farm's net investment rate (i.e. net investment in breeding stock divided by total breeding stock) is greater than two times the farm's median net investment rate of breeding stock over the study period (2007-2013). Previous studies (e.g. Kapelko *et al*., 2015; Geylani and Stefanou, 2013) defined investment spikes as a year in which the gross investment rate (i.e. gross investment divided by capital stock) is greater than 2.5 times the firm's median gross investment rate. This relative definition of spike avoids the effect of potential size differences. We assumed that a farm experiences genetic progress (i.e. uses cows with high genetic level compared to the population average genetic level, which is a shock to the system) in year *t* if an investment spike occurs in that year. This measure is used as a proxy for the genetic index of cows (total merit index of cows). We hypothesise that a high net investment rate of breeding stock has a positive effect on farm productivity growth as a result of the use of cows with better genetic potential.

The results of the impulse response analysis are presented in Table 6A.1. The impulse responses of input- and investment-specific dynamic productivity changes (and their components) to genetic progress using the measure of investment spike on breeding stock during the period 2007-2013 are estimated for five prediction horizons ($k = 5$). The results show that genetic progress results in a statistically significant increase in productivity growth associated with inputs and investments (except for feed in the first year), and then it leads to a decline in productivity growth in the third year.

Table 6A.1 Impulse responses of input- and investment-specific Luenberger dynamic productivity changes and their components to breeding stock investment spikes [a]

Years after spike (k)	LPC [b]	TC [c]	TIC [d]	SIC [e]
Feed				
1	-0.0069**	0.0076***	-0.0147***	-0.0005
2	0.0283***	0.0146***	0.0169***	-0.0032
3	-0.0009	0.0076**	-0.0267***	0.0087**
4	0.0009	-0.0089	0.0273***	-0.0037
5	0.0001	-0.0213	0.0153	0.0093
Other variable inputs				
1	0.0296***	0.0141	-0.0803***	-0.0030
2	0.0639***	-0.0044	0.0184	-0.0028
3	-0.1445***	-0.0151*	-0.1619***	-0.0125
4	0.0083	0.0012	0.1132***	0.0095
5	0.0085	-0.0011	0.0426	0.0029
Investment in capital				
1	0.2539	1.3901***	-0.7859**	-0.3384***
2	7.2389***	0.7807*	5.4884***	1.1579***
3	-0.9610	-1.0801**	-1.4018*	-0.5391***
4	-0.6290	-0.2241	-0.8146	0.0003
5	-0.1789	0.0289	0.3843	0.8833
Investment in breeding stock				
1	0.8913***	0.3180***	0.5792***	0.0392***
2	1.2209***	0.5633***	0.3471***	0.0114
3	-0.4546***	-0.0144	-0.1881*	-0.0218
4	-0.1693	-0.0101	-0.0383	0.0064
5	0.3407	0.1861	0.0287	0.0314

*** Significant at 1%; ** Significant at 5%; * Significant at 10%.

[a] According to this measure, if a farm's net investment rate of breeding stock in a given year is greater than two times the farm's median net investment rate in 2007-2013, a farm is assumed to experience genetic progress in that year. [b] Luenberger productivity change. [c] Technical change. [d] Technical inefficiency change under variable returns to scale. [e] Scale inefficiency change.

Chapter 7

General discussion

7.1 Introduction

Brazil is one of the biggest producers and exporters of pork in the world (ABCS, 2016). Pig farming is raising environmental and economic concerns, mainly associated with feed production and utilisation. Several studies proposed the use of alternative feed sources (e.g. Mackenzie *et al*., 2016; Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015b; Meul *et al*., 2012; Elferink *et al*., 2008) and genetic improvement of animals through selective breeding (e.g. Besson, 2017; Van Middelaar *et al*., 2014; Bell *et al*., 2013; Wall *et al*., 2010) for improving the environmental and economic sustainability of livestock farming. However, very little attention is given to: (1) the impacts of using alternative feed sources on the economic sustainability of pig farming in general, and on environmental and economic sustainability of Brazilian pig farming in particular; (2) the impact of genetic improvement of pigs on environmental sustainability; and (3) identification of breeding goal traits with their economic values (EVs) for Brazilian pig farming. Therefore, the main aim of this thesis was to assess the impacts of using locally produced alternative feed sources and genetic improvement of pigs on both environmental and economic sustainability of pig farming in Brazil.

In Chapter 2, environmental impacts of conventional and alternative feed ingredients were computed using a life cycle assessment (LCA). The cost-prices, environmental impacts and land use efficiency (i.e. opportunity cost of using arable land for feed production in terms of forgone human digestible protein from food crops) of different diet scenarios were also estimated. In Chapter 3 and Chapter 4, the impacts of innovations (i.e. alternative feed sources and genetic improvement) on the environmental and economic sustainability of Brazilian pig farming were assessed by combining LCA with bio-economic modelling. By considering greenhouse gases (GHGs) emission costs and the stochastic nature of key economic and biological parameters in the bio-economic farm model (Chapter 3), EVs of breeding goal traits were derived from a mean-variance utility function (Chapter 4). Chapter 5 presented the effects of using EVs that were derived by incorporating environmental costs and risk preferences of producers on response to selection (i.e. genetic gains of breeding goal traits, discounted economic returns and reductions in environmental impacts). Chapter 6 measured the effect of genetic progress on dynamic productivity growth and its components at farm level.

The remainder of this chapter is structured as follow. First, it presents the synthesis of the main results. Next, methodological approaches and data limitations are discussed. This is followed by the presentation of policy and business implications of the results. Then, potential avenues for future research are discussed. Finally, the main conclusions are listed.

7.2 Synthesis of results

In this section, the relevance of (i) utilising locally produced alternative feed ingredients and (ii) genetic improvement of pigs for enhancing the environmental and economic sustainability of Brazilian pig farming are addressed while considering trade-offs between economic and environmental performance, and between different environmental impact categories (e.g. land use versus global warming potential).

7.2.1 Replacing conventional feed ingredients by alternative feed sources

In the pig supply chain, feed production and utilisation (manure management) are the main hotspots of environmental impacts (Groen *et al*., 2016; Cherubini *et al*., 2015; Van Zanten *et al*., 2015b; Nguyen *et al*., 2012) and feed cost is the main component in the total cost of production (e.g. accounting for more than 75% in Brazil; Embrapa Swine and Poultry Centre, 2017). Several studies (e.g. Mackenzie *et al*., 2016; Van Zanten *et al*., 2015b; Meul *et al*., 2012; Elferink *et al*., 2008) proposed replacement of conventional feed ingredients by co-products in pig diets as one of the strategies for reducing the environmental impacts of pig farming. In line with the literature, the results of Chapter 2 showed that the use of co-products in pig diets reduces land use and GHGs emission associated with land use change (LUC). However, the results of Chapters 2 and 3 indicated that these improvements come with other environmental impacts such as emissions of GHGs and energy use, and higher expenses on feed as shown in Table 7.1 and Table 7.2. The summary in Table 7.1 presents the environmental impacts of feed production, and feed cost per kg body weight gain for different finishing pig diets: a reference diet (corn-soybean meal-based diet), macaúba diet (macaúba-based diet) and co-product diet (co-products-based diet). The results are presented for different economic allocations[4]. First, for a zero economic allocation to macaúba kernel cake (MKC) where MKC is considered as a waste with no economic value (only costs for processing and transport were considered) and second, for the case where MKC is considered as a co-product accounting for 5.4% of the total economic value of macaúba products (i.e. with 5.4% economic allocation to MKC).

With a 5.4% allocation of impacts to MKC, the macaúba-based diet slightly outperforms the reference diet in terms of feed cost and environmental impacts associated with feed production (except GWP; Table 7.1). However, even without allocating impacts to MKC, the macaúba-based diet is the worst in terms of GHGs emission associated with manure management (Table

[4]Economic allocation is the allocation of environmental impacts among the main product and co-products (e.g. for soybeans among the oil, meal and hulls) based on their relative shares in the total economic value of a product (Guinee *et al*., 2004).

Table 7.1 Environmental impacts of feed production and feed cost of finishing pig diets (expressed per kg body weight gain)

	Chapter 2			Chapter 3		
	Reference diet	Macaúba diet	Co-product diet	Reference diet	Macaúba diet	Co-product diet
With zero economic allocation to MKC						
GWP (kg CO_2-eq) [a]	1.49	1.18	1.34	1.46	1.24	1.41
Acidification (kg SO_2-eq)	0.05	0.04	0.04	0.06	0.05	0.04
Eutrophication (kg NO_3-eq)	0.12	0.10	0.10	0.12	0.10	0.10
Land use (m^2)	6.14	4.44	4.41	5.87	4.66	4.64
Energy use (MJ)	15.81	13.81	18.93	15.79	14.51	19.89
Feed cost (US$) [b]	0.62	0.53	0.59	0.49	0.44	0.50
With 5.4% economic allocation to MKC						
GWP (kg CO_2-eq) [a]	1.49	1.54	1.52	1.46	1.62	1.60
Acidification (kg SO_2-eq)	0.05	0.06	0.04	0.06	0.05	0.04
Eutrophication (kg NO_3-eq)	0.12	0.11	0.10	0.12	0.12	0.11
Land use (m^2)	6.14	4.65	4.52	5.87	4.88	4.75
Energy use (MJ)	15.81	15.01	19.53	15.79	15.77	20.52
Feed cost (US$) [b]	0.62	0.59	0.62	0.49	0.49	0.53
Nutritional values of diets						
Net energy (MJ/kg)	9.83	9.83	9.83	10.26	9.83	9.83
Std. dig. lysine (g/kg)	8.14	8.14	8.14	8.00	8.14	8.14
Feed intake (kg)	95.00	95.00	95.00	129.30	134.90	134.90
Net energy intake (MJ)	933.85	933.85	933.85	1326.62	1326.07	1326.07
Body weight gain (kg)	33.66	33.66	33.66	45.49	45.49	45.49

MKC, macaúba kernel cake

[a] Global warming potential including emissions from direct land use change.

[b] In Chapter 3, feed costs were derived based on average prices of feed ingredients over 2006-2015, whereas the feed costs in Chapter 2 were based on 2015 prices.

7.2). Although acidification and eutrophication impacts associated with manure management were not quantified in this thesis, the impacts are higher for the macaúba- and co-product-based diets as the excretions of nitrogen (N) and phosphorus (P) are higher for macaúba- and co-product-based diets than the reference diet (Chapter 3). The inclusion of different co-products in the diets of finishing pigs (the co-product-based diet) worsens all environmental impact categories except land use. Social profit (i.e. farm profit plus fertilizer equivalent value of manure minus GHGs emission costs from feed and manure management) is lower for a co-product-based system than for the current corn-soybean meal-based system when accounting for emissions from both feed production and manure management (Chapter 3).

Table 7.2 Global warming potential (GWP, kg CO_2-eq per kg body weight gain) of manure management for the different finishing pig diet cases

	Reference diet	Macaúba diet	Co-product diet
GWP	0.40	0.84	0.77

Source: Adapted from Chapter 3 (with no allocation of impacts to macaúba kernel cake).

In summary, when both feed production (Table 7.1) and manure management (Table 7.2) are considered, the use of co-products (including MKC) results in lower economic and environmental performances than the current corn-soybean meal-based system (except land use). The low economic performance might explain the very limited use of co-products in the current diets of pigs in Brazil, and for the negative perceptions towards the use of co-products that were voiced by farmers and other stakeholders (e.g. breeders and researchers) during various stakeholder project meetings and farm visits.

An evident advantage of utilising co-products in the diet of pigs (including MKC) is reducing the land use impact of pig farming, and thereby reduces the competition for arable land between crops used for food and feed (Chapter 2). This is important as livestock production currently uses one-third of global cereal production and occupies about 75% of agricultural land (Foley *et al*., 2011) while supplying only 33% of human protein consumption (Herrero *et al*., 2009). As the conversion of plant food sources (e.g. cereals) to animal food sources (e.g. pork) is inefficient (e.g. Van Kernebeek *et al*., 2015; Van Zanten *et al*., 2015a; Stehfest *et al*., 2009; Zhu and Van Ierland, 2004), the use of co-products in the diets of pigs makes arable land available for producing food crops for direct human consumption (Chapter 2) and thereby contributes to food security. The use of co-products that can be produced on marginal land (e.g. macaúba cake) improves the efficiency of pork production when marginal land is not used to grow food crops (Chapter 2). The increases in environmental impacts (e.g. GHGs emission and energy use) following from the use of co-products in pig diets are partly compensated by the increase in efficiency of food production due to the use of food crops for direct human consumption. Another possible advantage of utilising co-products in the diets of pigs is that farmers can reduce their dependence on corn and soybeans and this offers a possible substitution in case prices of soybeans and corn rise. Since the prices of corn and soybeans are determined in the global market, fluctuations of prices in the global market affects Brazilian pork production.

Even if the use of alternative feed sources (e.g. co-products) reduces some environmental (and economic) impacts such as land use and GHGs emission associated with LUC, lack of adequate economic benefits to producers may limit adoptions of these feed sources as the use of co-products raises feed cost (Chapter 3). Producers are expected to respond more to innovations (or incentives) that raise their private profits than to those that aim at raising societal welfare (e.g. environmental sustainability). For example, Kamali *et al*. (2014) reported that Brazilian soybean meal and beef business stakeholders, including farmers, perceive economic performance (e.g. profitability) to be more important than other sustainability issues whereas consumers and other stakeholders such as non-governmental organizations and institutions developing sustainability standards perceive social (e.g. food safety) and environmental issues to be more important, respectively. This suggests that innovations that aim at reducing environmental impacts at farm level should also contribute to economic performance of farms in order to increase their adoption rate.

7.2.2 Genetic improvement as a means for enhancing environmental and economic sustainability

Genetic improvement can be a possible pathway towards reducing the environmental impacts (i.e. GHGs emission, and excretion of N and P) of pig farming while improving farm profitability (Chapter 4, Chapter 5). The results of Chapter 4 also showed that raising productivity[5] via genetic change of traits (e.g. lowering feed conversion ratio (FCR)) raises the mean-variance utility of producers as an improvement in a trait (e.g. FCR) reduces both feed cost and its variance for a fixed level of output, while reducing environmental impacts (Chapter 4). However, raising production levels via genetic change of traits (e.g. increasing litter size) reduces the mean-variance utility of producers as it increases both output and variance of profit, while reducing environmental impacts per kg of body weight of finishing pig. In this case, mean-variance utility declines because the variance effect dominates the output effect (Chapter 4). Previous studies for dairy (Van Middelaar *et al*., 2014; Bell *et al*., 2013; Wall *et al*., 2010) and

[5] The phrases ‘raising productivity’ vs ‘raising production levels’ are widely used in this subsection. Raising productivity refers to raising farm output per unit of input used (e.g. increasing pork production per kg of feed used) whereas raising production levels refers to increasing output (e.g. increasing pork production per farm, increasing kg of live weight per finishing pig).

fish (Besson, 2017) farming systems showed that genetic improvement of animals via selective breeding reduces environmental impacts along the supply chain (e.g. global warming potential, eutrophication) while improving farm profitability. Unlike the use of alternative feed sources, which results in trade-offs between the different environmental impacts and with economic performance, genetic improvement of traits that raise farm productivity has the potential to reduce environmental impacts while improving the utility of risk averse producers.

Economic values provide signals about the direction and magnitude of changes in economic benefits and environmental impacts following from genetic change (Chapter 4). However, the ultimate effect of selection on economic benefits and environmental impacts depends, among other things, on heritability of traits, phenotypic and genetic correlations between traits, and the assumed breeding structure (Chapter 5). For example, although the EVs of pre-weaning piglet mortality (PWM) and weaning-oestrus interval (WOI) are negative, selection in a dam-line breeding objective (with breeding goal traits of average daily gain (ADG), litter size, PWM and WOI) resulted in increase in PWM and WOI (Chapter 5) when economic response to selection is optimised. ADG is more important than FCR in terms of relative EVs (economic weights; Chapter 4). However, in terms of response to selection, FCR is more important (Chapter 5).

Responses to selection based on EVs that have been derived while accounting for environmental costs, and risk and risk aversion are different from responses from traditional EVs[6] (Chapter 5). Responses derived from EVs that were estimated by accounting for environmental costs imply change in social profit[7] whereas responses derived from EVs that were estimated by accounting for risk and risk aversion imply changes in producers' mean-variance utility. Responses based on these alternative EVs are compared to responses based on the traditional EVs. Assuming a constant slaughter weight for finishing pigs and a fixed number of sows per farm, the use of EVs that are derived by incorporating environmental costs increases the cumulative discounted social profit in both sire-line (about 10%) and dam-line (about 5%) selections compared to response to selection based on the traditional EVs (Chapter 5). Discounted social profit obtained from improved FCR in a sire-line, for example, increases with the use of EVs that have been derived by accounting for environmental costs (Chapter 5) as an improvement in FCR reduces both feed cost and environmental costs associated with feed (Chapter 4). Similarly, an increase in litter size in a dam-line, for example, increases the efficiency of sows and thereby reduces feed cost and environmental costs per finished pig per

[6] Traditional EVs are derived without accounting for environmental impacts, and risk and risk preferences of producers.
[7] In this thesis, social profit refers to farm (private) profit plus fertilizer equivalent value of manure minus greenhouse gases emission costs from feed production and manure management (Chapter 3).

sow (Chapter 4). The use of EVs that are derived by accounting for risk and risk aversion increases the cumulative discounted mean-variance utility in the sire-line (by about 6%) while reducing it in the dam-line (by about 12%) compared to the use of traditional EVs (Chapter 5). Discounted mean-variance utility obtained from improved ADG in a sire-line, for example, increases with the use of EVs that have been derived by accounting for risk and risk aversion as an increase in ADG reduces feed cost and its variance (for a given level of output). On the other hand, a decrease in PWM in a dam-line, for example, increases both farm output and its variance, but the variance effect on mean-variance utility dominates (Chapter 4). Cumulative discounted economic response to selection from a dam-line selection is very small compared to the returns from a sire-line selection (Chapter 5). Among other things, this is due to a lower discounted number of expressions of reproduction traits (Brascamp, 1978). Similarly, the cumulative environmental impact reductions are higher in sire-line selection than in dam-line selection. Therefore, breeders need to give more emphasis to improving production traits than reproduction traits for raising, at the same time, the economic and environmental sustainability of pig farming.

Efficient land use is an integral component to ensuring food security (Godfray *et al.*, 2010). In this respect, genetic improvement of pigs via selective breeding can reduce the land use impact of the current system and thereby reduce the competition for arable land between crops used for pig feed and food. Chapter 4 demonstrated how genetic changes of production and reproduction traits reduce GHGs emissions, and excretions of N and P for a farrow-to-finish Brazilian pig farm with fixed number of sows and constant slaughter weight of finishing pigs. Similarly, genetic change of traits can reduce land use impact (Table 7.3). For a farming system with fixed slaughter weight and fixed number of sows, improvements in reproduction traits increase the absolute land use following from increase in production levels whereas improvements in production traits reduce land use following from increase in efficiency. Genetic changes of both production and reproduction traits reduce land use when expressed per final output (finished pig), which is a fair unit of analysis in environmental impact assessment (Van Arendonk, 2011). However, the reductions following from genetic change of reproduction traits are negligible compared to the reductions from genetic change of production traits. The results for the other environmental impacts (GHGs emission, and excretions of N and P; Chapter 4) are similar to those for land use. This is in line with the conclusions by Besson (2017: 157-158) who stated “ [...] selective breeding should focus on traits that contribute to better production efficiency rather than higher production”. This is especially true for risk averse producers as raising production levels (e.g. via genetic change of reproduction traits) reduces the utility of producers whereas raising production efficiency (e.g. via genetic change of production traits) increases their utility (Chapter 4).

Table 7.3 Effect of genetic change of traits by 1 genetic standard deviation (σ_G) on land use and key farm production variables relative to the situation without genetic change (per farm per year; adapted from Chapter 4)

Traits (unit)	σ_G	ΔNFP ($year^{-1}$)	ΔAge (days)	ΔFeed (kg/year)	ΔLU (m^2/year)	ΔLU (m^2/ finished pig)
NBA (per litter)	+0.90[a]	+2,504	0	+683,103	+1,438,419	-6.91
PWM (%)	-1.50 [a]	+550	0	+143,094	+313,783	-1.66
WOI (days)	-1.00 [a]	+224	0	+59,811	+120,766	-0.90
ADG (g/day)	+50.00 [b]	0	-5	-535,795	-1,139,629	-34.06
FCR (kg/kg)	-0.16 [b]	0	0	-522,144	-1,125,152	-33.63

NFP, number of finished pigs; Age, age of finished pig at slaughter; Feed, feed consumption by sows, piglets, growing and finishing pigs; LU, land use associated with feed production; NBA, number of piglets born alive; PWM, pre-weaning mortality rate of piglets; WOI, weaning-oestrus interval; ADG, average daily growth during the growing-finishing stage; FCR, feed conversion ratio during the growing-finishing stage.
[a] Rydhmer (2000)
[b] Gilbert *et al*. (2007)

The results of the gene flow method (Brascamp, 1978; McClintock and Cunningham, 1974) in Chapter 5 showed that the genetic superiorities (i.e. genetic changes) of selected parents that are transferred to their offspring decrease over time as the transfer of genes diminishes over generations. These results are not directly comparable to the results of the impulse response analysis (Chapter 6). However, the results of the impulse response analysis showed that expense on genetics (as a proxy for genetic change) increases productivity growth (and its components) of dairy farms in the first two years after the expense. Since the generation interval (or production cycle) is shorter in pig farming than in dairy farming, the effect of using high quality semen in pig farming is expected to materialise more in the first two years (compared to in dairy farming). The approach used in Chapter 6, i.e. input-specific dynamic productivity growth analysis combined with impulse response analysis, can also be applied for measuring the effect of genetic change on farm productivity growth and its components for (Brazilian) pig farming. To apply the approach in pig farming, farm level panel data on inputs, outputs and aggregate genotype of herds are required. Results described in Chapter 6 for dairy farming demonstrated that this is a promising avenue for evaluating the effect of genetic improvement in pig farming. The approach provides several pieces of information that could be used for improving the performance of dairy farms such as: (1) the evolution of the dynamic technical inefficiency scores associated with each input and investment over time, (2) identifying the factors of production (e.g. feed, other variable inputs, investments) that are the main sources of productivity growth and inefficiency changes, (3) identifying the main sources of productivity decline associated with each variable input and investment (i.e. decline in technical and scale efficiencies or technical regress), and (4) the effect of genetic progress on input- and investment specific productivity growths and their components over several years.

7.3 Methodological approaches

This section first discusses main assumptions made in this thesis. This is followed by a reflection on the multidisciplinary and interdisciplinary approaches applied in this thesis; the combination of bio-economic farm model with LCA for assessing the impact of innovations on private and social profits (Chapter 3); the derivation of EVs that account for environmental impacts (Chapter 4); and the dynamic productivity growth measure that was used in Chapter 6. The final subsection discusses the use of utility functions for deriving EVs by accounting for risk and the risk preferences of producers.

7.3.1 Main assumptions

The derivation of economic weights has been long discussed in the scientific literature and there is no generally accepted 'best' approach to be applied. Different approaches could estimate quite different values depending on the production system, the economic constraints, the breeding structures, the traits considered in breeding goals and the assumptions made. In this thesis (Chapter 4, 5), a typical farrow-to-finish pig farm with fixed number of sows (and constant slaughter weight for finishing pigs) was assumed for assessing the effect of genetic change of traits on economic and environmental sustainability of pig farming. The assumption of fixed number of sows influences the EVs of reproduction traits that are derived from utility functions (Chapter 4) and response to selection associated with breeding objectives that are defined using these EVs (Chapter 5). When a fixed number of sows is assumed, the importance of reproduction traits declines with risk aversion (Chapter 4) as an improvement in reproduction increases both farm profit and its variance, in which the effect of the variance on utility dominates (via a mean-variance utility function). However, if farm output (i.e. finishing pigs) is fixed instead of sows, less sows are required to produce the fixed output with genetic improvement of reproduction traits. In that situation, the EVs of reproduction traits would increase with risk aversion as feed cost and its variance associated with sows decline.

The conclusions associated with risk aversion for reproduction traits might slightly change, as described above, if the assumption of fixed number of sows is relaxed. However, even with fixed output, the efficiency gains (associated with feed) for reproduction traits is likely very small compared to the efficiency gains in production traits. As economic and environmental concerns of pig farming are mainly associated with feed and given the growing demand for animal protein (i.e. meat production needs to be increased), raising production levels with genetic improvements of reproduction traits and raising productivity with genetic improvements of production traits is the best strategy. For example, for the typical Brazilian farrow-to-finish pig farm with 1,500 sows (Chapter 4), increasing litter size by 1 genetic standard deviation leads to a decrease in the number of sows (by 34) for a fixed amount of output. Therefore, the main efficiency gains are associated with the reduction in feed consumption of these 34 sows (which is about 37,000 kg feed per year; Chapter 2). On the other hand, increasing ADG of growing-finishing pigs by 1 genetic standard deviation leads to a decrease in feed consumption of 535,795 kg per year for a fixed amount of output (Table 7.3). There is also evidence of negative genetic correlation between female fertility and feed efficiency, for example, in cattle farming (Ferreira Júnior *et al*., 2018). Therefore, breeders need to focus on increasing production levels in dam-line breeding objectives and raising productivity in sire-line breeding objectives as shown in this thesis to improve both the economic and environmental sustainability of pig farming (given the need for increased meat production).

7.3.2 Multidisciplinary and interdisciplinary approaches

Enhancing the sustainability of livestock farming via genetic improvement and nutritional management requires a close collaboration among different fields of science such as animal breeding, animal nutrition, economics and environmental science. This thesis followed multidisciplinary, interdisciplinary and mono-disciplinary approaches [8] to study the contributions of alternative feed sources and genetic improvement in improving the environmental and economic sustainability of livestock farming. The thesis itself provides a multidisciplinary and interdisciplinary approach to addressing the general research objective as it applied methods from various disciplines in the different chapters (Table 7.4). Enhancing the sustainability of livestock farming by using alternative feed sources (Chapter 2-3) and genetic improvement of animals (Chapter 4-6) reflects the multidisciplinary approach of the thesis. The integration of different fields of science (i.e. animal breeding, economics and environmental science) to define sustainable breeding goals (Chapter 4-5) reflects the interdisciplinary approach of the thesis.

The individual chapters followed interdisciplinary and mono-disciplinary approaches. Chapter 2 followed an interdisciplinary approach by integrating methods from the fields of animal nutrition (for formulating pig diets), environmental science (for estimating environmental impacts using LCA) and economics (for analysing (opportunity) cost). Chapter 3, which developed a stochastic bio-economic pig farm model, also followed an interdisciplinary

[8] According to a systematic discussion on multidisciplinary vs interdisciplinary approaches by Choi and Pak (2006), multidisciplinary research "draws knowledge from different disciplines but stays within the boundaries of those fields". Interdisciplinary research, on the other hand, "involves the interaction among two or more different disciplines and occurs at the interface between disciplines", which ranges from the sharing of ideas to full integration.

approach. The bio-economic farm model involved an integration of different fields of science (i.e. economics, animal nutrition, biology, environmental science). Chapter 4 and 5 also followed an interdisciplinary approach. The integration of animal breeding, economics and environmental science helped to define breeding objectives that improve both economic and environmental sustainability of pig farming by using EVs that have been derived by accounting for environmental costs, risk and the risk preferences of producers (Chapter 4-5). Chapter 6 used productivity and econometric analyses from the field of economics, which is a mono-disciplinary approach, to measure the effect of genetic progress on input-specific dynamic productivity growth.

Table 7.4 Overview of methods used in this thesis

	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Life cycle assessment (LCA)	×	×			
(Opportunity) cost analysis	×				
Bio-economic modelling		×	×	×	
Stochastic simulation		×	×		
Selection index method			×	×	
Dynamic productivity analysis					×
Econometric analysis					×

The combination of bio-economic farm model and LCA, which is an interdisciplinary approach, allowed for assessing the impacts of alternative feed sources (Chapter 3) and improved breeding materials (Chapter 4-5) on the economic and environmental sustainability of pig farming. Bio-economic farm models, which integrate biological, economic and management components of a system, have proven to be useful tools for assessing the impacts of innovations on technical, economic and environmental performances of farming systems (Janssen and Van Ittersum, 2007). The incorporation of a pig growth model, the InraPorc® model (Van Milgen *et al*., 2008) from the field of animal nutrition, into the bio-economic farm model allowed for assessing the impacts of using alternative feed sources on the technical performance indicators (e.g. daily growth, feed conversion, lean meat content, N and P depositions) of growing-finishing pigs (Chapter 3). By linking these technical performance indicators with LCA and cost analysis, the impacts of using co-products on private and social profits of a typical farrow-to-finish pig farm were assessed (Chapter 3). LCA is an internationally recognised and standardised method for assessing and evaluating the environmental impacts of products along their supply chains (Rebitzer *et al*., 2004).

The incorporation of the mitigation of environmental impacts in breeding goals allows breeders to contribute to the environmental and economic sustainability of farming systems (by integrating insights from the fields of animal breeding, economics and environmental science). In this thesis (Chapter 4, 5), sustainable breeding goals were defined by using EVs that were derived by incorporating GHGs emission costs into a bio-economic farm model, where GHGs emissions were monetized using a shadow price of CO_2. These EVs were derived by accounting for both economic and environmental components of a system. Previous studies of Besson (2017) for fish and Van Middelaar *et al*. (2014) for dairy farming systems employed a combination of farm models and the LCA technique for deriving separate EVs and environmental values[9]. Unlike the approach followed in this thesis, where environmental impacts are monetised, these studies derived the effects of genetic changes of traits on environmental impacts of a product (e.g. kg of milk or ton of fish) along the supply chain. Like EVs, the environmental values can be used to define breeding goals.

These two approaches of incorporating mitigation of environmental impacts in breeding goals (i.e. using EVs that are derived by accounting for environmental costs or using environmental values) have their own advantages and disadvantages. Accounting for environmental impacts in monetary terms allows for integrating economic and environmental components of a farming system into a single set of EVs. However, due to the absence of a well-functioning market for externalities (e.g. carbon emission allowance trading[10]), shadow prices were used for monetising environmental impacts. As a result, it is difficult to include all environmental impacts (e.g. land and energy uses) in monetary units as shadow prices are not available for some impacts. Even if they are available, there is a huge variation among the estimates, since a standardised and generally accepted method of estimation is missing (see Tol (2008) for an overview). On the other hand, the computations of separate EVs and environmental values for different traits are possible and provide signals about the direction and magnitude of changes in economic performance and environmental impacts. However, their application, for example, in multi-trait selection index is not simple. An animal that is selected based on EVs might not be selected based on environmental values due to trade-offs among economic performance

[9] An environmental value for a given trait refers to the difference in environmental impacts between a base situation (before genetic change) and a situation with genetic improvement of that trait while keeping the other traits constant (Besson, 2017; Van Middelaar *et al*., 2014). While economic values are expressed in monetary units, environmental values are expressed in units of environmental impacts (e.g. m^2 for land use and kg CO_2-equivalent for global warming potential).

[10] A system where an upper limit of emissions is fixed, and polluters that reduce their emissions compared to their allowance earn “credits” that they can sell to other polluters who would find it costly to reduce their emission, i.e. polluters are allowed to buy emission allowances from other polluters that can abate at lower costs (e.g. European Emission Trading System; www.oecd.org/environment/tools-evaluation/emissiontradingsystems.htm).

and environmental impacts. Similarly, an animal that is selected, for example, based on environmental values for global warming potential might not be selected based on environmental values for eutrophication potential. Therefore, incorporating environmental costs by monetising environmental impacts is considered a better approach for integrating mitigation of environmental impacts in breeding goals as it helps to account for trade-offs. However, reasonable shadow prices, specific to a given production region, should be used for monetising environmental impacts as shadow prices reflect the damage costs that release of pollutants (e.g. GHGs emission) cause to the environment, human health and economy/resources. Moreover, the impacts of some environmental issues (e.g. eutrophication and acidification) are limited to specific regions.

A mono-disciplinary approach (i.e. based on the field of economics) was also followed in one of the chapters of this thesis (i.e. Chapter 6)[11]. The Luenberger dynamic productivity growth indicator was used to estimate input-specific dynamic productivity growth. In general, there are two types of productivity growth measurements that are used in productivity analysis: ratio-based measures (e.g. Malmquist productivity growth index) and difference-based measures (e.g. Luenberger productivity growth indicator). Several studies (e.g. Briec and Kerstens, 2004; Boussemart *et al*., 2003; Managi, 2003) showed that ratio-based indices overestimate productivity growth compared to difference-based productivity growth indicators. In addition, the ratio-based measures are problematic when the values of the denominator are zero. The Luenberger productivity growth indicator (Chambers *et al*., 1996), however, overcomes these shortcomings. The Malmquist productivity indices are either input or output oriented while the Luenberger productivity indicator can simultaneously contract inputs and expand outputs, but can also measure in either input or output orientations (Boussemart *et al*., 2003). Furthermore, unlike the ratio-based measures (e.g. Malmquist), the Luenberger measure of productivity growth can be decomposed into technical inefficiency change, scale inefficiency change and technical change. The decomposition provides several pieces of information for identifying sources of productivity decline (e.g. Kapelko *et al*., 2017, 2015; Oude Lansink *et al*., 2015). A systematic discussion on ratio- vs difference-based measures of productivity growth can be found in Chambers (2002, 1998) and Diewert (1998).

7.3.3 Profit equations, bio-economic models vs utility functions

Economic values are required for selecting animals that contribute to economic and environmental sustainability. Economic, biological and bio-economic approaches are the three common approaches for estimating EVs (see Nielsen *et al*. (2014) for an overview). The

[11] The chapter would have followed an interdisciplinary approach if data on aggregate genotype of herds were obtained.

economic approach is based on a simple profit equation by identifying traits associated with the returns and costs of pig production (e.g. Brascamp *et al*., 1985). The economic approach does not take into account the physiological impacts of a change in a trait. On the other hand, the *biological approach* uses information on the physiological characteristics of pigs, neglecting the economic impact of a change in the value of a trait (e.g. the composite trait lean tissue feed conversion of Fowler *et al*. (1976)). A trait which could be improved using the biological approach might not contribute to profitability. The *bio-economic approach* combines both the economic and biological approaches to define a breeding goal. Bio-economic models are increasingly used to estimate EVs of breeding goal traits as they provide a more accurate and complete description of production systems than profit or biological models (e.g. De Vries, 1989; Houška *et al*., 2004). Both profit or bio-economic models that are commonly used for deriving EVs in the literature, however, do not take into account the risk present in the production system and the risk preferences of producers. Risk is an integral component of agricultural production following, for example, from input-output price volatility, yield variability (e.g. due to weather, diseases), change in consumer preferences, institutional and policy changes (Hardaker *et al*., 2015). Uncertainties associated with such factors affect investment, production and other farming decisions (Taya, 2012; Tangermann, 2011) as most farmers can be considered risk averse (Hardaker *et al*., 2015; Moschini and Hennessy, 2001).

Since innovations (e.g. improved breeding materials, feeding strategies) not only affect farm profit but also variance of profit (Just and Pope, 1978), EVs should be derived from utility functions (by integrating risk and risk preferences into bio-economic models; e.g. from mean-variance utility functions). These utility functions enable us to better capture the behaviour of farmers compared to using either profit or bio-economic models. For example, two technologies may be expected to increase farm profit but their effect on the variability of farm profit may be different. Risk averse producers would prefer the technology that results in less variability, even though this entails a lower return (i.e. they are willing to pay a risk premium). EVs that are derived from utility functions imply that breeders need to emphasize more on genetic changes of efficiency traits in sire-lines rather than increasing reproduction levels in dam-lines (Chapter 4). To increase the accuracy of these EVs, however, the actual risk preferences of producers should be estimated for a given production system. There are several techniques for eliciting risk preferences such as direct elicitation using lottery games, econometric approaches based on observed behaviour and mathematical programming techniques (e.g. O'Donoghue and Somerville, 2018; Hardaker *et al*. (2015); Charness et al., 2013).

7.4 Data limitations

The main data related limitations faced in this thesis are listed as follows:

- The life cycle inventory data for feed production and utilisation were based on literature sources. Some of these life cycle inventories (e.g. emission factors, allocation rates) are not specific to Brazil. Moreover, there are no life cycle inventory data for macaúba kernel cake (MKC) as it is an emerging product (Chapter 2). For missing life cycle inventories, data from different databases (e.g. ecoinvent, agri-footprint, FeedPrint) were used. The absolute results would, therefore, be different if specific values are obtained for Brazil. However, since the thesis focused on comparisons of scenarios (e.g. reference vs co-products-based diets), the conclusions may not be affected. In addition, most of the life cycle inventory analyses (e.g. outputs, emission factors) in this thesis (and in the literature) are based on 1-year data or for some variables (e.g. prices and outputs) based on averages of annual values. Due to several factors (e.g. weather conditions, institutional and policy changes, management changes), parameter values in the life cycle inventory analyses (e.g. outputs, prices, emission factors) vary over time. Therefore, LCA estimates from these life cycle inventory analyses for a certain production year fail at representing the actual environmental performances of farming systems for several years. Therefore, the robustness of results would increase if LCA analyses were done in a time series framework (i.e. conduct LCA analyses for each production year on the basis of life cycle inventory data from each year).
- The amino acid compositions of MKC were based on the compositions of macaúba pulp cake (Chapter 2). The digestibility coefficients of its chemical constituents were based on palm kernel meal, i.e. a similar palm co-product. The results associated with MKC could, therefore, change slightly if data specific to MKC were available.
- Stochasticity of prices of feeds and finishing pigs, and biological variations between growing-finishing pigs were considered in this thesis (Chapter 3). However, there are also other sources of risk in pig farming that are not considered due to lack of data. For example, mortality of pigs (especially during the growing-finishing phase) and outbreak of diseases might be important sources of risk.
- To measure the effect of genetic progress on dynamic productivity growth at farm level, a good measure of genetic progress (i.e. aggregate genotypes (total merit indices) of herds) is required. In this thesis (Chapter 6), expense on artificial insemination was used as a measure of genetic progress. Data on total merit index, which is a linear function of economically important traits, are required to accurately measure genetic progress.
- If farm level data on inputs, outputs and genetic progress for (Brazilian) pig farming were obtained, the focus of Chapter 6 would be measuring the effect of genetic progress on

productivity growth of pig farming in Brazil (since the focus of the four chapters of this thesis (Chapter 2-5) is on Brazilian pig farming). Data from dairy farms were used in this thesis for measuring the effect of genetic progress on farm productivity growths and their components (Chapter 6). However, if data are obtained for pig farming, the approach can be directly followed to measure the contribution of genetics to (Brazilian) pig farm productivity growth.

7.5 Policy and business implications

Policy implications

The results of Chapter 2 indicated that the current system of pork production in Brazil is not efficient as it requires a large area of arable land (and high quality food crops). Policy makers may encourage the use of plant food sources (e.g. cereals), which are currently being used in pig production, for direct human consumption as more protein can be obtained from direct consumption rather than through raising pigs (Chapter 2). Therefore, policy makers may stimulate a consumption shift from pork that is produced using food crops to plant food sources.

The land use ratio results for the current corn-soybean meal-based and for the co-products-based systems (Chapter 2) imply that the production of pork using co-products (and marginal land) can make cropland available for food crops production for direct human consumption. Therefore, policy makers could stimulate the utilisation of co-products in the diets of pigs for improving food security. Furthermore, policy makers may encourage the use of co-products in the diets of pigs to reduce deforestation for growing soybeans and thereby reduce environmental impacts (e.g. GHGs emission) associated with LUC.

Since the use of EVs that have been derived by accounting for GHGs emission costs improves both economic and environmental sustainability of pig farming (Chapter 5), policy makers may facilitate the design of a well-functioning carbon market for the agricultural sector or may impose taxes on farms for emission of GHGs or excretion of nutrients. A carbon market (e.g. the European Emission Trading System) allows agents (e.g. farmers) to trade emission allowances, and thereby environmental impacts become part of farming decisions via market forces (e.g. like feed cost). Similarly, producers might be obliged to pay taxes for emission of GHGs or excretion of nutrients.

The negative dynamic technical changes for investments in both capital and breeding stock for Dutch specialised dairy farms (Chapter 6) might be due to higher costs to comply with restrictive regulations (e.g. environmental regulations regarding manure disposal and emission reducing measures), which impose higher costs but do not add directly to production. In that case, policy makers may relax those restrictive regulations such that farmers can also make productive investments. Moreover, policy makers may encourage research that aims at developing technologies that increase farm productivity while reducing environmental impacts (e.g. a technology that improves pasture productivity while reducing nitrate and phosphate leaching).

Business implications

Although the use of co-products in the diets of pigs improves land use efficiency (Chapter 2), it results in lower economic and environmental performances than the current corn-soybean meal-based system when both feed production and manure management are considered (Chapter 2, 3), i.e. both farm and social profits are lower for the co-products-based systems. Therefore, Brazilian pig farmers may continue farming with the current corn-soybean meal-based system.

Following the growing public scrutiny of current livestock production systems, there is a growing effort and interest to improve sustainability of pig farming. Breeding companies can play a role in improving the sustainability of pig farming through selective breeding. As shown in this thesis (Chapter 4, 5), the use of EVs that have been derived by accounting for environmental costs enables breeders to include mitigation of environmental impacts in broad breeding goals by improving animal productivity and efficiency. Reductions in environmental impacts following from genetic change of reproduction traits are negligible compared to the reductions from genetic change of production traits (Chapter 5). Therefore, breeders need to give more emphasis to selection for production traits (e.g. FCR) than reproduction traits (e.g. litter size) as (economic and social) returns are higher in sire-line selection than in dam-line selection. Moreover, breeders need to give more emphasis in raising productivity rather than production levels in order to significantly reduce environmental impacts (Chapter 5).

Risk is an integral component of agricultural production. The use of EVs that have been derived by accounting for risk and the risk preferences of producers enables breeders to select animals that would reduce the impact of risk on farm performance (Chapter 4, 5). Breeders need to give more emphasis to selection for raising productivity rather than raising production levels in order to reduce variability for a given level of output (i.e. to maximize the utility of risk-averse producers). In general, in order to improve both the economic and environmental sustainability of Brazilian pig farming while contributing towards the need for increased meat production (Chapter 5), breeders need to consider: (i) both environmental impacts and farmers' risk aversion in sire-line breeding objectives by raising productivity, and (ii) only environmental costs in dam-line breeding objectives by raising production levels.

Since most of the environmental and economic problems of pig farming are associated with feed production and utilisation (Groen *et al*., 2016; Cherubini *et al*., 2015; Van Zanten *et al*., 2015b; Nguyen *et al*., 2012), breeders need to give more emphasis to improvement in feed efficiency (Chapter 5). Breeders may use different strategies such as the use of information from crossbred animals (on top of information from purebreds on which current selections are based on) to increase the genetic gain of feed efficiency as shown by Godinho *et al*. (2018). Moreover, improving the accuracy of feed intake measurements in pigs may help breeders to obtain more genetic gains in feed efficiency.

The negative dynamic technical changes for investments in capital and breeding stock for Dutch specialised dairy farms (Chapter 6) might be attributable to higher costs of inputs for complying with environmental regulations. If this is the case, farmers have to be incentivised to invest in technologies that increase productivity (via technical progress) and reduce environmental impacts (i.e. they need to balance productive and unproductive investments). The results of the impulse response analyses (Chapter 6) showed that spending more than the median expense on genetics increases productivity growth associated with inputs and investments in the first two years after the expense. Therefore, Dutch dairy farmers may increase productivity associated with inputs and investments by spending more than their median expenditure on genetics.

7.6 Future research

This thesis focused on economic and environmental sustainability of pig farming. Future studies may conduct an integrated sustainability assessment by also covering the social (e.g. food safety, animal welfare, child labour) dimension of sustainability, besides the economic (e.g. profitability) and environmental (e.g. emissions, biodiversity, soil quality) dimensions. Then the effects of using alternative feed sources and genetic improvements of animals can be assessed on all the different dimensions of sustainability.

In this thesis, the roles of alternative feed sources in enhancing the environmental sustainability of pig farming were assessed using an attributional LCA, where the environmental impacts of a product are estimated throughout its life cycle (e.g. for feed, from extraction of raw materials for growing feed ingredients until its utilisation at a pig farm). The use of existing co-products (e.g. wheat middlings, sugarcane molasses) for replacing corn and soybean meal in pig diets might affect other sectors (e.g. beef farming). Displacing co-products from, for example, beef farming to pig farming causes the use of other ingredients (e.g. soybean meal) in beef farming, which might even be more detrimental from environmental impact point of view. Therefore, a consequential LCA study is required to see the full picture of using alternative feed sources (e.g. co-products) in pig diets at a system level (by accounting for the competing applications of feed sources).

Co-products are often considered as inferior products to use in pig feed production in Brazil whereas they are widely used in other parts of the world (e.g. the Netherlands)[12]. Future studies may find out the reasons behind these perceptions. In this thesis, the role of genetic improvement in improving the economic and environmental sustainability of the conventional production system, which relies on corn and soybean meal for feed, was assessed (Chapter 4 and 5). However, breeding objectives can also be designed for alternative production systems, which use alternative feed sources (e.g. co-products). For example, improving the digestive capacity of pigs via selection can reduce the excretions of volatile solids, N and P associated with low quality diets (e.g. co-products). Animal nutritionists may also work to increase the digestibility of these low-quality (fibrous) feed ingredients. Therefore, future researches may study the roles of nutritional and genetic improvements in the utilisation of alternative feed sources. The effect of alternative feed sources on meat quality was also not considered in this thesis. A recent study by Li *et al*. (2018), for example, showed that the use of low-protein diets in growing-finishing pig diets increases meat quality through the regulation of intramuscular fat content and fatty acid compositions.

Future research may explore the heterogeneity in risk preferences of Brazilian pig producers, which can be used to increase the accuracy of EVs that are derived from utility functions as shown in this thesis. Previous studies have shown that risk preferences vary greatly between different regions, individuals and decision domains. Measuring the risk attitudes of producers also provides information for designing innovations and policies according to producers' preferences. This helps to increase the adoption rates of innovations that aim at improving the sustainability of production systems.

In Chapter 3, it is assumed that available farm resources (e.g. buildings and equipment) are optimally used and the farm operates at its optimum. In Chapter 4, fixed costs are treated as variable costs when computing the effect of genetic change on farm profit (assuming that all factors of production are variable in the long run and since genetic improvement is also for the long run). However, a genetic change may also lead to changes in farm management and the

[12] Until now there is no scientific literature on the perception of inferior quality of co-products to use in pigs' diets. But with personal communications with researchers from a Brazilian university (Universidade Federal de Viçosa) and Brazilian Agricultural Research Corporation (Embrapa), it is understood that producers, but also several researchers, have a negative attitude towards using co-products. It is also understood from farm visits that producers are hardly using any co-products. There is a strong culture of dependence on corn and soybeans.

optimum may change. Future studies may study the effect of genetic change by considering environmental impacts and risk aversion with an optimised management.

7.7 Main conclusions

The main conclusions of this thesis are:

- The use of co-products in the diets of pigs in Brazil raises feed costs, global warming potential, energy use, and excretions of N and P (Chapter 2, 3), and reduces land use (Chapter 2).
- Production of human digestible protein in Brazil via raising pigs requires four to five times the area of land needed for the production of the same quantity of human digestible protein via growing food crops (Chapter 2). The use of co-products that can be produced on marginal land (e.g. macaúba cake) improves the efficiency of pork production when marginal land is not used to grow food crops (Chapter 2).
- The combination of a bio-economic farm model with LCA enables for assessing the impacts of using alternative feed sources and improved breeding materials on economic and environmental sustainability of pig farming (Chapter 3, 4) and for deriving EVs by accounting for environmental impacts and economic performance (Chapter 4).
- Since EVs that are derived by accounting for risk and risk aversion are different from EVs that are derived from traditional bio-economic farm models, breeders need to account for risk and risk aversion in order to serve risk averse producers (Chapter 4).
- Breeders need to focus more on genetic changes of traits that increase farm productivity rather than on traits that increase farm output in order to raise the utility of risk averse producers (Chapter 4, 5).
- The use of EVs that are derived by accounting for environmental costs enables to define breeding goals that simultaneously contribute to the economic and environmental sustainability of Brazilian pig farming (Chapter 4, 5).
- Cumulative reductions in environmental impacts (emissions of GHGs, and excretions of N and P) following from genetic change of traits in a dam-line breeding objective are very small compared to reductions in a sire-line breeding objective (Chapter 4, 5).
- Higher expense on genetics increases productivity growths associated with inputs and investments in the first two years after the expense for Dutch dairy farms (Chapter 6).

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Summary

Brazil is one of the biggest producers and exporters of pork in the world. Pig farming is raising environmental and economic concerns, mainly associated with feed production and utilisation. It causes major environmental impacts due to its strong dependence on scarce resources (e.g. cropland, fossil fuel and water), and release of pollutants to the atmosphere, soil and water. Pig farming relies heavily on high quality food crops (i.e. cereals and oilseeds). In recent years, the growing competition for these feed ingredients with other sectors such as the energy and food sectors has resulted in rising feed costs. The problem of rising feed cost is exacerbated by price volatility of cereals and oilseeds. Several studies proposed the use of alternative feed sources and genetic improvement of animals via selective breeding for improving the environmental and economic sustainability of livestock farming. However, very little attention is given to: (1) the impacts of using alternative feed sources on the economic performance of pig farming in general, and on the environmental and economic sustainability of Brazilian pig farming in particular; (2) the impact of genetic improvement of pigs on environmental sustainability; and (3) identification of breeding goal traits with their economic values (EVs) for Brazilian pig farming. Therefore, the main aim of this thesis was to assess the impacts of using locally produced alternative feed sources and genetic improvement of pigs on both the environmental and economic sustainability of pig farming in Brazil.

Chapter 2 assessed the environmental and economic impacts of utilising co-products in the diets of pigs in Brazil. Three diet scenarios were defined, i.e. (1) a reference scenario with a standard corn-soybean meal-based finishing diet, (2) a macaúba kernel cake-based scenario and (3) a co-products-based scenario. The environmental impacts (global warming potential, land and energy uses) of these diet scenarios were estimated using the life cycle assessment (LCA) method. Results show that inclusion of co-products in the diets of pigs has the potential to reduce the environmental impacts of pork production, particularly land use and the global warming potential when land use change is included. Compared to the reference scenario, land use per finished pig is 10% lower for the alternative scenarios. Global warming potential per kg live weight is 3.4-7.0% lower for the alternative scenarios when direct land use change is included whereas it is about 6-7% lower when indirect land use change is included. Energy use is 4.4% lower for the macaúba-based scenario whereas it is 7.0% higher for the co-products-based scenario. The use of co-products that can be produced on marginal land (e.g. macaúba cake) improves the efficiency of pork production when marginal land is not used to grow food crops. The land use ratio results (4.84 for the reference scenario and 4.35 for the alternative scenarios) imply that the production of pork using co-products can make cropland available to produce food crops for direct human consumption. Compared to the reference scenario, feed costs are lower by 4.4% for the macaúba kernel cake-based scenario and by

1.5% for the co-product-based scenario. However, the results for global warming potential and feed costs are sensitive to the economic allocation rate of macaúba kernel cake.

Chapter 3 developed a stochastic bio-economic pig farm model for assessing the impact of innovations on private and social profits. By combining bio-economic modelling with LCA, the developed model accounted for emission of greenhouse gases (GHGs) from feed production (Chapter 2) and manure management. It also accounted for the stochastic nature of key economic and biological parameters. The model was applied to assess the impact of using locally produced alternative feed sources (i.e. co-products) in the diets of finishing pigs on private and social profits of a typical Brazilian farrow-to-finish pig farm. Three cases were defined: (1) a reference case (with a standard corn-soybean meal-based finishing diet), (2) a macaúba case (with a macaúba kernel cake-based finishing diet), and (3) a co-products case (with a co-products-based finishing diet). Pigs were assumed to be fed such that net energy intakes were equal in the three cases. Social profits are 34% to 38% lower than private profits in the three cases. Private and social profits are about 11% and 14% higher for the macaúba case than the reference case whereas they are 3% and 7% lower for the co-products case, respectively. Environmental costs are higher under the alternative cases than the reference case. The coefficient of variation of farm profits is between 75% and 87% in the three cases following from the volatility of prices over time and variations in biological parameters between fattening pigs.

Chapter 4 proposed a method for integrating environmental costs and risk preferences of producers into the estimation of EVs of breeding goal traits for improving both economic and environmental sustainability of pig farming at the same time. A breeding goal consisting of both sow reproductive efficiency as well as production traits was defined for a typical Brazilian farrow-to-finish pig farm with 1,500 productive sows. A mean-variance utility function was employed for estimating the EVs at finishing pig level assuming fixed slaughter weight by extending the stochastic bio-economic pig farm model (Chapter 3). Results show that economic weights that are derived by accounting for risk and risk aversion are lower for reproduction traits (17%) and higher for production traits (7%) than the traditional economic weights. Similarly, economic weights that are derived by accounting for environmental costs are lower for reproduction traits (3%) and higher for production traits (1%) than the traditional economic weights. Genetic changes of breeding goal traits by 1 genetic standard deviation unit reduce emissions of GHGs, and excretions of nitrogen (N) and phosphorus (P) per finished pig by up to 6% while increasing farm profit. The estimated EVs can be used to improve selection criteria and at the same time contribute to the sustainability of pig production systems.

Chapter 5 assessed the effects of using those EVs which were derived by accounting for environmental costs and risk preferences of producers (Chapter 4) on discounted economic response to selection and on environmental impacts at commercial farm level. The application focuses on Brazilian pig production. Separate dam- and sire-line breeding programs that supply parents in a three-tier production system for producing crossbreds (fattening pigs) at commercial level were assumed. The use of EVs that are derived from mean-variance utility functions by accounting for risk and risk aversion increases the cumulative discounted utility in sire-line selection (6%) while reducing response in dam-line selection (12%) compared to the use of traditional EVs. The use of EVs that are derived by accounting for environmental costs increases the cumulative discounted social profit in both dam-line (5%) and sire-line (10%) selections. Emission of GHGs, and excretion of N and P for the typical Brazilian farrow-to-finish pig farm can be reduced more with genetic improvement of production traits than with genetic improvement of reproduction traits. Breeders need to consider both environmental costs and risk preferences of producers in sire-line selection to simultaneously improve the economic and environmental sustainability of Brazilian pig farming. In dam-line selection, only environmental costs need to be considered.

Chapter 6 measured the effect of genetic progress on dynamic farm productivity growth and its components. Impulse response analysis was used to measure the effects of farm expenses on genetics, on input- and investment-specific dynamic productivity growths and their components. The empirical application focused on panel data of Dutch specialized dairy farms over 2007-2013. Results show that productivity growth associated with breeding stock is negative (-1.2%), suggesting that the potential for doing investments in breeding stock has declined by 1.2% per year over the sample period for given levels of inputs and outputs. Technical changes associated with investments in capital and breeding stock are also negative. The results of the impulse response analysis show that expense on genetics leads to increase in productivity growth associated with inputs and investments in the first two years after the expense. The approach followed in this chapter is a promising avenue for evaluating the effect of genetic improvement for (Brazilian) pig farming when data for this can be collected.

The main conclusions of this thesis are:

- The use of co-products in the diets of pigs in Brazil raises feed costs, global warming potential, energy use, and excretions of N and P (Chapter 2, 3), and reduces land use (Chapter 2).
- Production of human digestible protein in Brazil via raising pigs requires four to five times the area of land needed for the production of the same quantity of human digestible protein via growing food crops (Chapter 2). The use of co-products that can be produced on

marginal land (e.g. macaúba cake) improves the efficiency of pork production when marginal land is not used to grow food crops (Chapter 2).

- The combination of a bio-economic farm model with LCA enables for assessing the impacts of using alternative feed sources and improved breeding materials on economic and environmental sustainability of pig farming (Chapter 3, 4) and for deriving EVs by accounting for environmental impacts and economic performance (Chapter 4).
- Since EVs that are derived by accounting for risk and risk aversion are different from EVs that are derived from traditional bio-economic farm models, breeders need to account for risk and risk aversion in order to serve risk averse producers (Chapter 4).
- Breeders need to focus more on genetic changes of traits that increase farm productivity rather than on traits that increase farm output in order to raise the utility of risk averse producers (Chapter 4, 5).
- The use of EVs that are derived by accounting for environmental costs enables to define breeding goals that simultaneously contribute to the economic and environmental sustainability of Brazilian pig farming (Chapter 4, 5).
- Cumulative reductions in environmental impacts (emissions of GHGs, and excretions of N and P) following from genetic change of traits in a dam-line breeding objective are very small compared to reductions in a sire-line breeding objective (Chapter 4, 5).
- Higher expense on genetics increases productivity growths associated with inputs and investments in the first two years after the expense for Dutch dairy farms (Chapter 6).

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Beshir Ali
November 01, 2018

Curriculum vitae

About the author

Beshir Ali was born on 17 November 1985 in Meragna, Ethiopia. In July 2007, he completed his Bachelor study in Economics at Haramaya University (Ethiopia). In the same year, he joined Mizan-Tepi University (Ethiopia) as a graduate assistant and worked for a year. In September 2008, he pursued his MSc study in International Economics at Addis Ababa University (Ethiopia) and completed with distinction (*Cum Laude*) in July 2010. Thereafter, he returned to Mizan-Tepi University and worked as a lecturer until January 2013. In February 2013, he started his second MSc study in Organic Agriculture with specialisation in Consumer and Market at Wageningen University & Research , and completed with distinction (*Cum Laude*) in January 2015. Next, he started his PhD research at the Business Economics Group of Wageningen University & Research in the LocalPork Project. He was a visiting scholar for two months (January - February 2018) at University of Florida, USA. For the coming two years (2019 and 2020), he will work as a postdoc at the Business Economics Group of Wageningen University & Research.

Peer reviewed publications

Ali B. M., van Zanten, H. H. E., Berentsen, P. B. M., Bastiaansen, J. W. M., Bikker, P. and Oude Lansink, A. G. J. M. (2017). Environmental and economic impacts of using co-products in the diets of finishing pigs in Brazil. *Journal of Cleaner Production* 162, 247-259.

Ali, B. M., Berentsen, P. B. M., Bastiaansen, J. W. M., & Oude Lansink, A. G. J. M. (2018). A stochastic bio-economic pig farm model to assess the impact of innovations on farm performance. *Animal,* 12 (4), 819-830.

Ali, B. M., de Mey, Y., Bastiaansen, J. W. M., & Oude Lansink, A. G. J. M. (2018). Effects of incorporating environmental cost and risk aversion on economic values of pig breeding goal traits. *Journal of Animal Breeding and Genetics*, 135(3), 194-207.

Ali, B. M., Bastiaansen, J. W. M., de Mey, Y., & Oude Lansink, A. G. J. M. (2018). Response to a selection index including environmental costs and risk preferences of producers. *Accepted in Journal of Animal Science.*

Ali, B. M., de Mey, Y., & Oude Lansink, A. G. J. M. The effect of genetics expenses on dynamic productivity growth. *Under review in European Review of Agricultural Economics*.

Conference proceedings

Ali, B. M., Berentsen, P. B. M., Bastiaansen, J. W. M., & Oude Lansink, A. (2017). A Stochastic Bio-Economic Farm Model for Brazilian Farrow-to-finish Pig Production System. Contribution presented at the XV EAAE Congress, “Towards Sustainable Agri-food Systems: Balancing Between Markets and Society”, August 29th – September 1st, 2017, Parma, Italy.

Ali, B. M., van Zanten, H. H., Berentsen, P. B. M., Bastiaansen, J. W. M., Bikker, P., & Oude Lansink, A. G. J. M. (2017). Assessing the Economic and Environmental Impacts of Utilizing Existing and New Co-products in Brazilian Pig Diets. Contribution presented at the XV EAAE Congress, “Towards Sustainable Agri-food Systems: Balancing Between Markets and Society”, August 29th – September 1st, 2017, Parma, Italy.

Ali, B. M., de Mey, Y., Bastiaansen, J. W. M., & Oude Lansink, A. G. J. M. (2017). Effects of incorporating environmental cost and risk preferences on economic values of pig breeding goal traits. Contribution presented at the 7th EAAE PhD workshop, “Challenges for young agro-food and natural resource economists facing the future”, November 8th – 10th, 2017, Castelldefels, Barcelona, Spain.

Training and supervision plan

Beshir Melkaw Ali
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
Advanced microeconomics, ECH-32306	ECH, WUR	2015	6
Genetic improvement of livestock, ABG-31306	ABG, WUR	2015	6
Sustainable development of animal systems: Issues & options, APS 30306	APS, WUR	2015	6
Writing of the PhD research proposal	WUR	2015	6
WASS summer school: Theory and practice of efficiency & productivity measurement	WASS	2017	3
B) General research related competences			
Introduction course	WASS	2015	1
Techniques for writing and presenting a scientific paper (TWP)	WGS	2015	1.2
Risk analysis and risk management in agriculture: Updates on modelling and applications	WASS	2017	2
PhD discussion group	BEC, WUR	2015-2018	2
'*A stochastic bio-economic farm model for Brazilian farrow-to-finish pig production system*'	XV EAAE Congress, Parma, Italy	2017	1
'*Assessing the economic and environmental impacts of utilizing existing and new co-products in Brazilian pig diets*'	XV EAAE Congress, Parma, Italy	2017	1
'*Effects of incorporating environmental cost and risk preferences on economic values of pig breeding goal traits*'	7th EAAE PhD workshop, Castelldefels, Spain	2017	1
C) Career related competences/personal development			
Portuguese language training (beginner)	Radboud in'to Languages, Nijmegen	2015	1.3
Teaching (Advanced financial business economics (BEC-50306) and Advanced business economics (BEC-30306), practical)	BEC, WASS	2015, 2017, 2018	1.5
Total			**39**

*One credit according to ECTS is on average equivalent to 28 hours of study load

Colophon

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Propositions

1. Including co-products in the diets of pigs raises land use efficiency of Brazilian pig farming at the cost of global warming potential, energy use and farm economic performance.
   (this thesis)

2. Breeders can simultaneously reduce the environmental impacts of pig farming and raise the utility of risk averse farmers by focusing on traits that increase farm productivity.
   (this thesis)

3. Reducing food losses along the food supply chain massively boosts the sustainability of food production.

4. The economies of developing countries can benefit more from curbing illicit capital flights than from development aids.

5. Attracting competent teachers is crucial to save the rapidly collapsing Ethiopian education system.

6. The current global fight against terrorism is a serious threat to democracy.

Propositions belonging to the thesis, entitled:
'Enhancing the environmental and economic sustainability of pig farming: The case of Brazil'
Beshir Melkaw Ali
Wageningen, 21 December 2018