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Future global pig production systems according to the Shared Socioeconomic Pathways

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Abstract

Global pork production has increased fourfold over the last 50 years and is expected to continue growing during the next three decades. This may have considerable implications for feed use, land requirements, and nitrogen emissions. To analyze the development of the pig production sector at the scale of world regions, we developed the IMAGE-Pig model to describe changes in feed demand, feed conversion ratios (FCRs), nitrogen use efficiency (NUE) and nitrogen excretion for backyard, intermediate and intensive systems during the past few decades as a basis to explore future scenarios. For each region and production system, total production, productive characteristics and dietary compositions were defined for the 1970–2005 period. The model shows that, despite the improvement of FCRs during the 1970–2005 period has reduced the feed use per kg of product, total feed demand has increased by a factor of two (from 229 to 471 Tg DM) due to the growing pork production. The increase of nitrogen use efficiency was slower than the improvement of FCRs due to increasing protein content in the feed rations. As a result, total N excretion increased by more than a factor of two in the 1970–2005 period (from 4.6 to 11.1 Tg N/y). For the period up to 2050, the Shared Socio-economic Pathways (SSPs) provide information on levels of human consumption, technical development and environmental awareness. The sustainability of pig production systems for the coming decades will be based not only on the expected efficiency improvements at the level of animal breeds, but also on four additional pillars: (i) use of alternative feed sources not competing with human food, (ii) reduction of the crude protein content in rations, (iii) the proper use of slurries as fertilizers through coupling of crop and livestock production and (iv) moderation of the human pork consumption.

Introduction

The contribution of pigs and poultry to total livestock production has increased worldwide over the last 50 years, driven by rising demand for livestock products, specialization, automation, production and trade of cheap feedstuffs, market liberalization, cheap energy and improved technologies in genetics and feeding strategies (Gerber et al. 2010). The global production of edible protein, in the form of nitrogen (N) from monogastric animals (pigs and poultry) increased from 1.1 to 6.8 Tg yr^{-1} between 1961 and 2013 and their contribution to total animal source food from 30 to 53% in the same period (Lassaletta et al. 2016). Pig production is expected to increase significantly during the next three decades (Alexandratos and Bruinsma 2012) (Supplementary material, SM-1). The increasing demand for pork is driven by population growth as well as the dietary transition towards more animal protein per capita (Lassaletta et al. 2014a, Bai et al. 2018).

Pigs are produced in a variety of systems, ranging from backyard to intensive systems, with different levels of technical development and diverse feed sources, varying from local products and swill to internationally traded feed products (Macleod et al. 2013, 2017). Both small-scale and large-scale farms are important sources of food for consumers, but they often differ in terms of efficiency, output and resource consumption (Samberg et al. 2016; Herrero et al. 2017). In 2005, 34% of the global pig stock was kept in backyard systems and 54% in intensive systems, while intermediate systems (12%) were less frequent (Robinson et al. 2014).

The increase in pork production has consequences for the use of natural resources. On the one hand, pig production systems have better feed conversion ratios (FCRs) and higher N use efficiency (NUE) than ruminants (Bouwman et al. 2005; Gerber et al. 2014; Hou et al. 2016), resulting in lower feed demand and lower N excretion per unit of product (Velthof et al. 2015). On the other hand, unlike ruminants, pigs cannot digest significant amounts of natural grasses and cellulosic crop fibrous residues, and their rations contain more food crop-based feedstuffs than those of ruminants, increasing feed–food competition

(Eisler et al. 2013). The recent growth of pig production has therefore induced a rapid increase in the feed demand, including cereals and oil crops (Foley et al. 2005; Lassaletta et al. 2014b; Wang et al. 2018).

There are several environmental issues related to pork production along the production-supply chain (Winkler et al. 2016). Several N compounds are emitted to the air and soil and during the production of feed crops, animal production and manure management (Uwizeye et al. 2016). Another issue is related to agricultural land use, which is expanding globally, partially to produce the required amounts of feed for the increasing livestock sector (Doelman et al. 2018).

The composition of feed rations is an important factor determining the sustainability of pig production due to 1) the requirement for substantial land surfaces for feed crop production (Uwizeye et al. 2016), 2) competing claims on food/feed by humans and livestock (Schader et al. 2016), and 3) the effect of various feed rations on the amount of N excreted, nitrous oxide and ammonia emitted, and nitrate leaching to groundwater (Sanchez-Martin et al. 2017; Sajeev et al. 2018). Lassaletta et al. (2016) estimated that feed demand of monogastric systems – measured in protein – is currently about one-third of total crop production (not including grass). However, part of the feedstuff for livestock consists of nonedible products such as by-products from the food and bio-fuel industry and household swill (Mottet et al. 2017). In particular, the use of alternative feedstuffs can potentially reduce feed demand, avoid wastes and promote nutrient recycling. Currently, there is an increasing use of proteins from wastes or by-products of the food industry (Sánchez-Muros et al. 2014; Veldkamp and Bosch et al. 2015; Salemdeeb et al. 2017). At the same time, relevant improvements in feed efficiency may be achieved from feed technologies by reducing the crude protein (CP) content in diets and replacing it with synthetic amino acids (Apple et al. 2017), using additives such as prebiotics, probiotics and enzymes such as proteases (Martínez Álvarez et al. 2015; Hou et al. 2015), and genetic improvements using new technologies (Barrangou and Doudna 2016).

In addition to improved feeding practices, good health and herd management as well as proper manure management can reduce the environmental impact of pig production (Mottet et al. 2016). Indeed, improvements in the production performance of intensive systems during the last few decades have increased the efficiency at both the animal and herd levels, resulting in important feed savings (e.g., Bai et al. 2014; Harchaoui and Chatzimpiros 2017). Moreover, manure management systems vary between systems and also within intensive systems (Willems et al. 2016), and the growing intensive pork production causes a rapid increase of manure production, which adds to the need to improve manure management. One of the problems in many countries is a geographical concentration of pork production, which results in limited cropland without the possibility to recycle all manure produced, creating a local shortage of available land for efficient recycling of manure as a fertilizer (Strokal et al. 2016; Willems et al. 2016).

Thus, the potentially different trajectories that the pig sector will follow during the coming decades concerning total production, management and feed composition will have a substantial effect on the sustainability of the global agro-food system. Recent papers have explored potential future developments considering the livestock sector as a key component for the future sustainability of the whole system (e.g., Davis and D' Odorico 2015; Frank et al. 2018; Bai et al. 2018; Springman et al. 2018). Some of these studies (van Vuuren et al. 2017; Doelman et al. 2018) have examined the response of the system to the storylines of the five Shared Socioeconomic Pathways (SSPs, Riahi et al. 2017), which represent possible future demographic and economic development trajectories towards alternative future human societies (O'Neill et al. 2017). The objective of this article is to analyze the global and regional development of the pig production sector including effects of feed rations, feed demand, nutrient use efficiency and excretion during the past few decades (1970–2005) as a basis to explore future changes (2050). To explore the development in the coming decades, we use alternative scenarios for demand and production of pork in 2050 following the SSP storylines, as inputs into a new module (IMAGE-Pig) developed for the IMAGE 3.0 integrated assessment model (Stehfest et al. 2014).

2. Methods

2.1 IMAGE and the pig module (IMAGE-Pig)

IMAGE 3.0 is an integrated assessment modeling framework that simulates the interactions between human activities and the environment to explore long-term global environmental change and policy options in the areas of climate, land and sustainable development (Stehfest et al. 2014). Economic and demographic development for 26 regions drive human activities such as energy and food production (SM-1). Food demand and trade come from the MAGNET model (Woltjer and Kuiper 2014). To assess the impacts of food production and wastewater discharge, IMAGE includes the Global Nutrient Model (GNM), which describes the global N and P flows, including agricultural fertilizer and manure management and the fate of nutrients in the atmosphere and hydrosphere (Beusen et al. 2016). In livestock production systems, IMAGE distinguishes five animal categories (dairy, beef, pigs, poultry and small ruminants) and two production systems (mixed and industrial, and pastoral) (Bouwman et al. 2005). Feed demand, efficiency and nutrient excretion are calculated per year and per animal class and system.

IMAGE-Pig provides a detailed representation of pig production distinguishing three systems based on their production intensity and technology: backyard, intermediate and intensive. Backyard systems are partially enclosed, devoted to subsistence or local markets and their feed rations include a large share of swill and on-farm available feedstuffs. Intermediate systems are partially enclosed and they are market-oriented with an intermediate level of capital input using on-farm and off-farm feedstuffs and in some cases internationally traded feedstuffs. Intensive systems are fully enclosed, market-oriented and typically have a high level of capital input, and rations are made up of off-farm purchased feedstuffs from within the country or imported from abroad (Macleod et al. 2013).

IMAGE-Pig has four submodules (the Meat Module, Herd Module, Energy Module and Nutrient Retention Module, Fig. 1 and SM-1). The model uses 35 input parameters (two production parameters, 16 production performance parameters and 17 parameters for feedstuffs) and 78 constants (see supplementary material for a detailed description of the model and its parameterization). IMAGE-Pig is parameterized per region, system and year. The pig module of IMAGE was programmed in FORTRAN, post-processing analyses were performed in R (R-Core Team 2014).

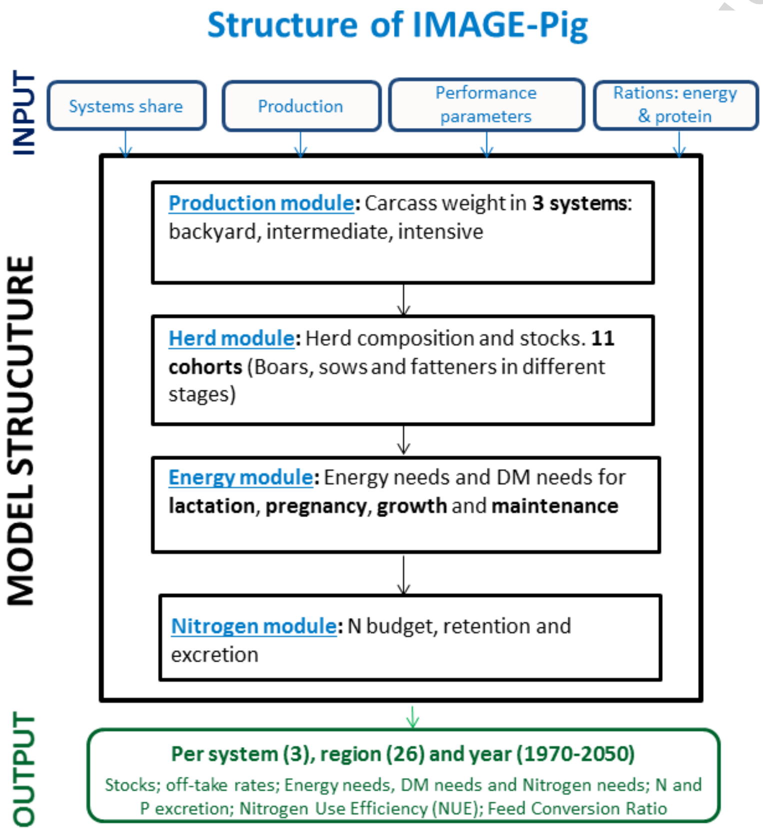

Fig. 1. Structure of the IMAGE-Pig model for IMAGE 3.0.

The historical input parameters come from statistical data in FAOSTAT (FAO, 2017) and several other sources. Some parameters were obtained from MacLeod et al. (2013) for the year 2005. Some modifications of these parameters were based on an extensive literature review (see Methods and SM-

1), and following a number of assumptions and rules (see SM-1). For example, assumptions to transform available data for specific regions not equivalent to the IMAGE region definition, parameterization of years other than the base year 2005 (namely 1970, 1990, 2015 and 2050), or to determine parameters not included in Macleod et al. (2013). The model calculates animal stocks, feed demand per feedstuff, efficiency indicators and N excretion per system, region and year. The key parameters for demand, system type, farm productivity and feed use that were adapted for the historical representation and for the scenario construction were: total production, fraction of the production for each system, carcass weight, average daily growth of fatteners, litter size (number of piglets per litter), litters per sow and year, and feed rations. Other parameters were slightly different depending on the region and system, but for this study they were assumed to be constant for the historical years and scenarios. Since the sector is evolving rapidly, we use performance parameters updated to 2015 for the present moment.

2.2 The four submodules

The meat module estimates the amount of meat (kg of carcass per year) produced per system (backyard, intermediate and intensive) and IMAGE region by multiplying the total carcass weight (CW) produced per year and region (AGRPRODAN, based on FAO and IMAGE calculations) by the proportion of meat produced at each system and region (FRPROD, see SM-1 for a complete description of the equations).

To obtain FRPROD per year and region, we used the pig density maps per system as provided in Geo-Wiki for 2005 (Robinson et al. 2014). The total number of heads per region was corrected to fit FAOSTAT stocks per IMAGE region. Next, IMAGE-Pig is run iteratively to arrive at similar stock numbers. For the historical construction, we assumed the amount of backyard production to be stable within each region for the whole period. This is consistent with the structural change described by Steinfeld et al. (2006) which calls for a stagnation of backyard production systems during the last decades in favour of more intensive systems. For most world regions (e.g., Latin America, East Asia) the industrialization of pig production occurred after 1990; in Europe, the USA and Australia this transition mainly took place in the 1980s (Cameron 2000; Schneider et al. 2011; Bai et al. 2014).

The herd module calculates the stocks and the off-take rates. This module describes the functioning of the herd considering 11 different cohorts including fatteners, sows, boars and gilts at different stages (see SM-1). CW from FAOSTAT was used to estimate the number of animals slaughtered per year, region and system to determine the number of animals needed to achieve a specific meat production level (AGRPRODAN) within each cohort. Since CW from FAOSTAT is a weighted average of the CW from different systems, several rules (see SM-1) were used to determine CW for the three systems and 26 IMAGE regions. Key parameters such as litter size (Fig. 2) and the number of litters/sow/year for different regions, and productive systems were derived from a comprehensive literature review (Lañada et al. 1999; Kunavongkrit and Heard 2000; Wabacha et al. 2004; Chimonyo et al. 2006; Kumaresan et al. 2007; Nakai 2008; Phengsavanh et al. 2010; Hoste 2011; Bai et al. 2014; AHDB 2016).

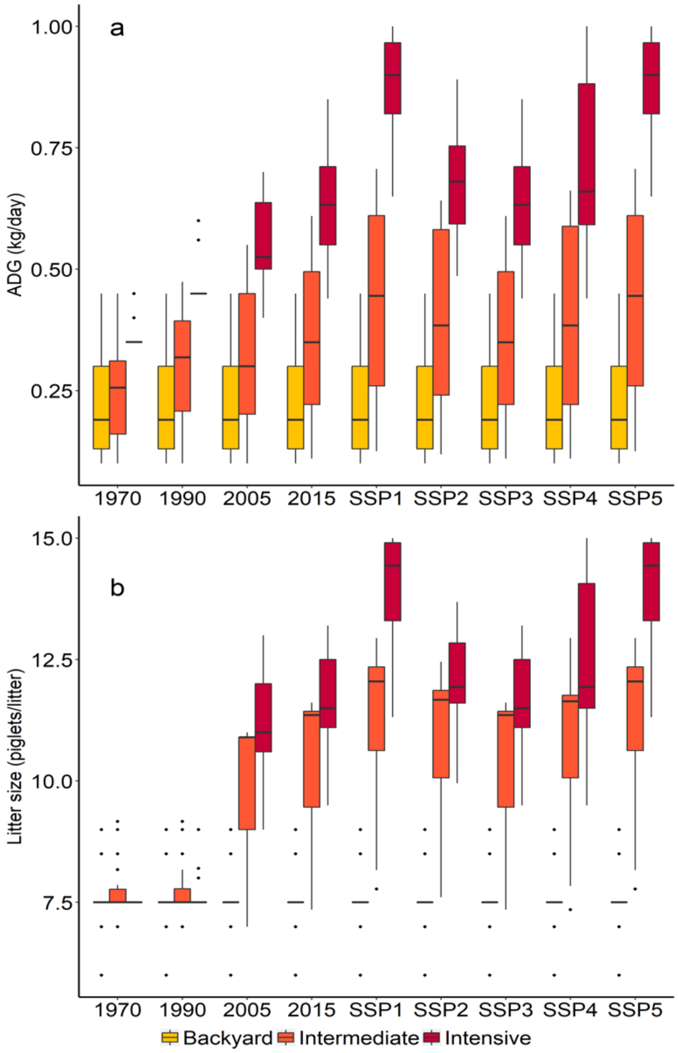

Fig. 2. Box plot representation of a) global average daily weight gain (ADG) and b) litter size (piglets per litter) used to parameterize historical years and 2050 projections per system in the 26 IMAGE regions. In b) the values for the backyard system are depicted by black dots.

The energy module calculates the total energy requirement per year, cohort, system and region. Following the IPCC (2006) approach, the energy requirement for each cohort (h) of the herd was determined according to recommendations by Noblet et al. (1990), NRC (2012) and FEDNA (2013) considering the needs for lactation (MEl), gestation (MEp), growth (MEg) and thermoregulation (MEt) and using information on period length (days) and weight gain (kg) per cohort (see SM-1). The inputs needed for this module include animal weight, weight gain, time period within each cohort, and housing temperature. Average daily weight gain (ADG, Fig. 2) for fattening animals and other parameters were obtained from the literature (Cole et al. 1994; Pérez 1997; Wabacha et al. 2004; Lemke et al. 2006; Simongiovanni et al. 2009; Phengsavanh et al. 2010; Averos et al. 2012; Vincek et al. 2012; Agostini et al. 2014; Bai et al. 2014; BPEX 2014; Riedel et al. 2014; Douglas et al. 2015).

The N module estimates the N retained, the total N excretion, the excretion rates (kg N/head/year, at the herd level) and N use efficiency (NUE). This module calculates the N retained in growth (Ng), milk production (Nm) and pregnancy (Np), the total N input in the diet by cohort (see SM-1). N excretion per cohort (N_{EXCRET}) is calculated as the difference between N intake (N_{INTAKE}) and N retention (N_{RET}).

2.3 The feed rations

The feed rations were formulated considering 17 feedstuffs that include feeds competing with human food (namely, temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops and others) and materials and by-products that are not edible by humans (including brans, distiller’s dried grains with solubles (DDGS), forage, molasses, swill, animal-source feed, swill-industrial/household residues, synthetic amino acids and other residues). Two nutritional attributes are considered for each feedstuff: 1) energy content expressed as metabolizable energy (ME) for pigs (MJ/kg dry matter [DM]); 2) crude protein content (CP content as a percentage of DM). Specific ME contents for pigs and protein content of each feedstuff were obtained from Feedipedia.org and Sauvant et al. (2004). The categories considered include several crop groups (e.g., temperate cereals can be wheat, barley and oats). We weight-averaged the nutrient content based on the contribution of each feedstuff per category (e.g., barley use in the cereals category) to feed uses provided in the FAOSTAT Food Balance Sheets for the base year (2005). These nutritional attributes are provided in SM-1. The energy and N content of the final rations is calculated considering the composition of the feedstuffs and the energy and protein content of each ingredient. Total dry matter ingestion was calculated by dividing the total energy demand by the energy content of the ration.

The feed rations for 2005 were defined for intensive systems as follows:

i) We assumed diets as proposed by MacLeod et al. (2013) adapted to IMAGE feed categories as a baseline for all regions, except for the China+ region where information from Bai et al. (2014) was used.

ii) We used the composition of the feed availability provided in the Food Balance Sheets, adjusted to the IMAGE regions to modify the rations according to the availability of each group (particularly grains) of feed for each of the 26 IMAGE regions.

iii) Subsequently, recommendations from Meisinger (2010), NRC (2012) and FEDNA (2013) were followed to keep feed ingredients within recommended ranges for all regions.

iv) Finally, DDGS were introduced for the USA and Canada following Meisinger (2010), Stein and Shurson (2008) and Mackenzie et al. (2016).

Rations were modified for previous years according to variations in historical FAO feed allocation and the gradual increasing share of oil crops (mainly soy products) over the years. For backyard systems, swill, residues and fibrous products were considered as the basis for pig feed for all regions based on a literature review (Saadullah and Saad 2000, Lemke et al. 2006, Kjos et al. 2010; Phengsavanh et al. 2010, zu Ermgassen et al. 2016). Data on feed allocation by FAOSTAT was also used to define the inclusion of other ingredients. Rations and performance for backyard production were considered to be constant from 1970 onwards, assuming that increased demand for pork will cause a transition to intermediate and intensive systems rather than an improvement of backyard systems. Finally, intermediate systems' rations were calculated as an average between intensive and backyard rations for all regions (See dataset SM-2).

2.4 Parameterization for 2050 for the five SSPs

The five SSPs include contrasting population growth, wealth, environmental concerns, policy, technological development and dietary preferences, and have recently been equipped with IMAGE 3.0 (Van Vuuren et al. 2017; Doelman et al. 2018). SSP1 represents the “green growth” paradigm scenario with low population growth, high agricultural efficiency (crops and livestock) and high environmental awareness. SSP2 represents the middle of the road scenario, while SSP3 represents a fragmented world with technological stagnation and a large population. SSP4 describes an unequal world with regions evolving according to contrasting pathways, based on SSP1, SSP2 or SSP3. Finally, SSP5 is a world where economic development is based on fossil fuels, technological improvements are rapid and environmental awareness is low (Table 1). The region-specific development of food consumption patterns (including meat consumption) was based on a GDP increase per region using the MAGNET model (Doelman et al. 2018). IMAGE-Pig was parameterized for 2050 following the spirit of these storylines (Table 1). In SSP1 there is a general reduction of the per-capita pork demand in industrialized countries and a moderate increase in the rest of the world. There is a general improvement of the farm performance of intensive systems and a preference for replacing soybean and other human edible feed crops by non-human edible feeds. SSP5 is similar to SSP1 for farm performance, but the per-capita consumption is high and no preference for non-human edible crops is considered. SSP2 intermediate lies between SSP1 and SSP5 in terms of productivity and pork consumption. Productivity improvement in SSP3 stagnates and per capita consumption is high, particularly in industrialized countries.

The input parameters used for the scenarios for 2050 in intensive systems were based on two criteria: firstly, the technical upper limits were considered to be achieved for all parameters and secondly, different evolution pathways for regions were defined, leading to a convergence towards a high productivity scenario in all regions. Similar to historical years, the parameterization of backyard systems assumes constant values. Performance of intermediate systems was expected to improve parallel to intensive evolution maintaining the current distance.

Litter size is assumed not to exceed 15 piglets per sow and partum. Considering the need of nursing sows due to the limited number of nipples (around 13–14 today), we assumed that it is not technical-economically feasible to increase this value over the average value of 15 (Ocepek et al. 2017). Regarding the number of litters per sow and per year, an upper limit of 2.4 was assumed (Ocepek et al. 2017). This was based on the interval between each partum comprising the gestation (115 days), lactation (around 28 days) and post-lactation anestrus *anoestrum* (minimum 4-5 days) periods yielding 2.47 litters per sow (Soede et al. 2012). However, we assumed that under practical conditions a value of 2.4 is more plausible. We assume a limit of 1000 g/day of weight gain during the whole fattening period. Such values have recently been achieved in some cases for industrialized regions (e.g., the USA and Western Europe). Lower values for upper limits for litter size and weight gain were taken for SSP2, leading to modest improvements compared to SSP1 and SSP5. All parameters for SSP3 are fixed at the current levels. Several assumptions were made to regionalize this trend (see SM-1).

Future rations vary depending on the expected impacts of breeding, nutrition technologies and consumer demands. Breeding technologies aim at improving nutrient use efficiency (Kyriazakis, 2011; Patience et al., 2015), while nutrition research focuses on providing nutrients to animals more efficiently, for example by using enzymes (Zijlstra et al. 2010). Under SSP1, improvements in animal efficiency and nutrient re-use would reduce the use of oil crops as protein sources. These could be partly replaced by alternative protein sources such as food processing residues from the food industry (Fig. 3). Adding feed enzymes to improve nutrient utilization would be a standard practice under SSP1, SSP2 and SSP5. The use of enzymes (Habte-Tsion et al. 2018) and technological treatments (Schedle 2018) in brans and other ingredients have already demonstrated relevant improvements in energy use by monogastric animals. The use of enzymes will make it possible to feed animals larger shares of by-products mostly considered under the “brans,” “swill-industrial/household” and “molasses” categories (Zijlstra et al. 2010; Kiarie et al. 2013). Consequently, the ME values of this alternative feed are assumed to be 20% higher than current ones (Ugwuanyi 2016; Jinno et al. 2018). In addition, improvements in digestive performance would increase ME by 10% for the other feed ingredients (except synthetic amino acids). Following these principles, a weighted average of the ME increase was calculated and applied to the final ME of the ration.

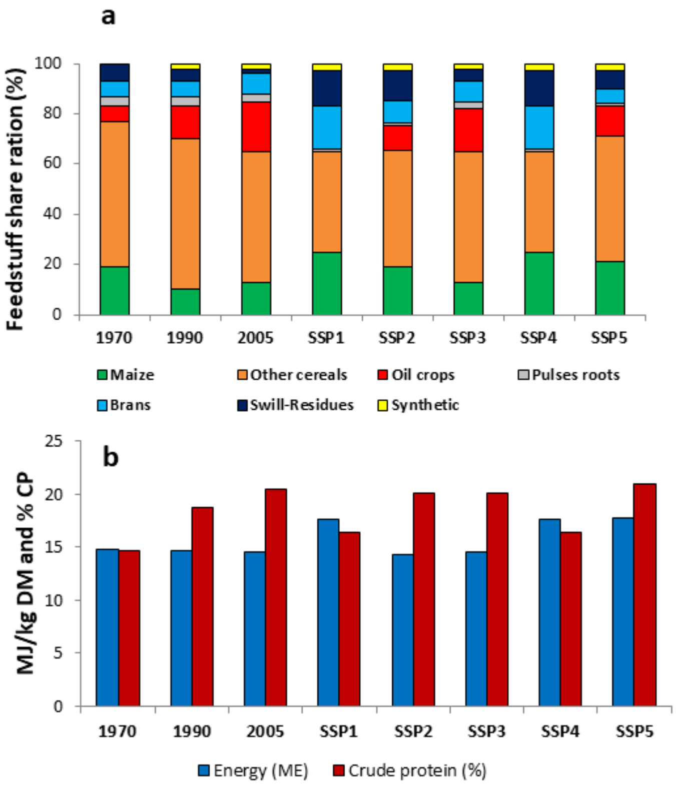

Fig. 3. a) Feed rations for feedstuffs (grouped into seven large categories) and b) energy content (MJ of metabolizable energy/kg DM) and percent of crude protein (CP) content for historical years and projections for 2050 according to the SSP scenarios for intensive systems in Western Europe.

2.5 Validation and sensitivity analysis

IMAGE-Pig was calibrated for the base year (2005) and then validated with pig stocks from FAOSTAT. Pig stocks were aggregated to the level of the 26 IMAGE regions. The Nash–Sutcliffe model efficiency coefficient was calculated to compare FAOSTAT and IMAGE estimates for all years from 1970 to 2016. For all other parameters there are no globally and regionally consistent data for validation. The plausibility of the IMAGE-Pig was therefore based on literature comparisons. The sensitivity of the pig module was investigated using Latin Hypercube Sampling (LHS) for 57 model variables and constants. With this technique, samples are taken within a range determined for each parameter to compute a range of model outputs. The standardized regression coefficient (SRC) was calculated to show the contribution of each input parameter to the variance of the model outputs.

3. Results

3.1 Production

In all five SSPs pig meat production is expected to increase rapidly in the 2010–2050 period (99 Tg of CW in 2010 (Fig. 4). The maximum increase was calculated for SSP5 (207 Tg of CW in 2050) due to population growth from 6.5 to 8.6 billion people between 2005 and 2050 and the increasing per capita consumption (from 15.5 kg in 2010 to 24 kg/cap/year in 2050). Lower growth in pork demand is projected for SSP1 (126 Tg of CW in 2050), mainly associated with the slow population growth (8.5 billion people in 2050), and a slight decrease in global average pork consumption, which is the combined effect of a decrease in consumption in “industrialized” countries and an increase in pork consumption in developing regions.

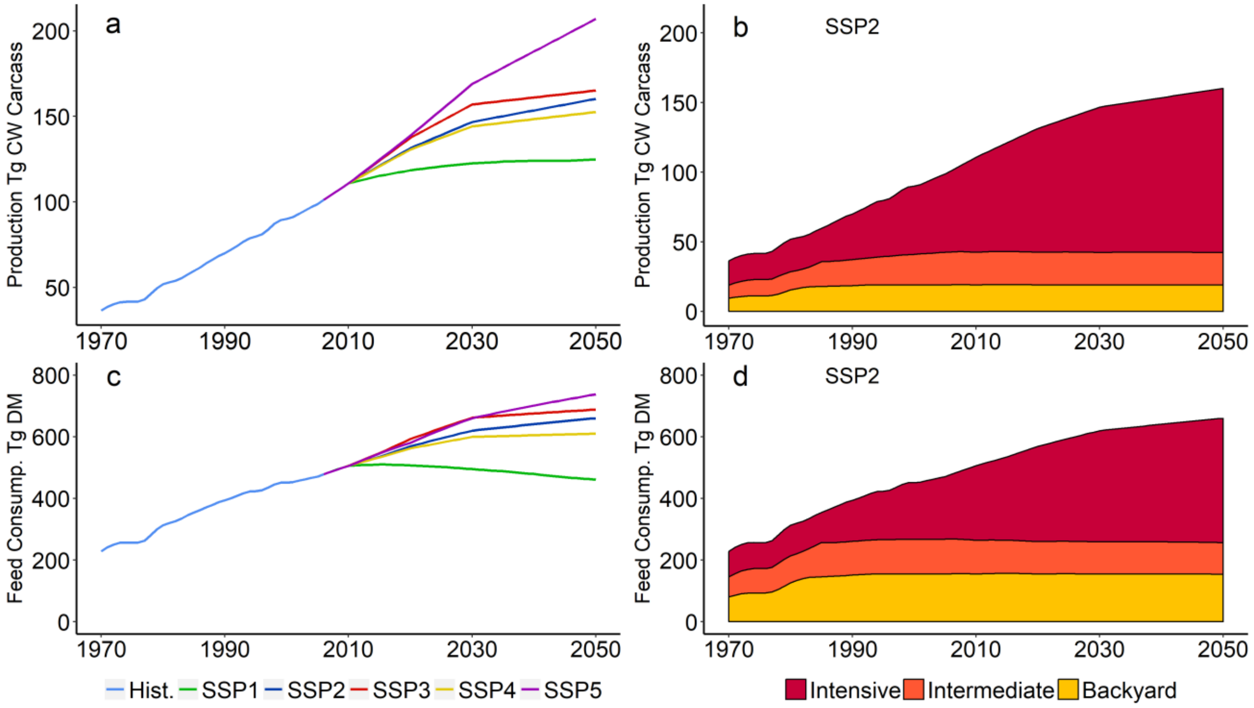

Fig. 4. Trajectories for global pig production and global feed requirements of pig production systems for the five SSPs (a, c); and pork production and feed demand for the SSP2 scenario for backyard, intermediate and intensive systems (b, d).

In 2005, 47% of global pig production was concentrated in China, 19% in Western Europe and 10% in the USA. The share of Chinese production is projected to increase to 52–58% of world production in 2050. In 2005 19% of total pork production corresponded to backyard systems, 24% to intermediate and 57% to intensive systems. Backyard systems are important only in Africa and Southeast Asia. In 2050 the contribution of backyard and intermediate systems is projected to decrease in all scenarios, with a range of 10–13% for backyard production. The production in intermediate systems in 2050 ranged from 13% to 15%. Consequently, the production in intensive systems in 2050 exceeds 70% of the total in all scenarios.

3.2 Feed use

The calculated feed demand has doubled during the last three decades from 226 Tg DM in 1970 to 471 Tg DM in 2005 (Table 2). Compared to the 2005 level, this demand is expected to increase in all SSPs with the exception of SSP1 (461 Tg DM). The maximum increase (34%) was estimated for SSP5 (752 Tg DM). Due to the lower feed conversion ratio of the backyard systems (associated with lower performance and diets including more swill; see section 3.4) the feed demand of pigs in 2005 accounted for 32% of total feed use, while pig production was 20% of global production. In all SSPs the feed intake of backyard and intermediate systems stagnates.

In 2005, pigs consumed 144 Tg DM of cereal grains globally, with 17% maize and 12% temperate cereals such as wheat and barley. Between 1970 and 2005, the proportion of oil crops such as soybean and rapeseed increased twofold from 12 Tg to 48 Tg DM, equivalent to 3.6 Tg N and accounting for 27% of total protein produced in soybean production worldwide. Feed use by pigs was concentrated in China (39%) and Western Europe (25%), because these two regions reared more than 65% of the global pig production (Fig. 5). In SSP2, SSP3 and SSP5, the demand for oil crops is expected to increase to 63, 83 and 75 Tg DM, respectively. Only in SSP1 is a significant reduction of the oil crop demand projected (14 Tg DM). In SSP1 some regions, such as Europe and the USA, oil crops would be replaced by alternative protein sources such as processed food residues and new sources of protein, together with the generalization of the use of synthetic amino acids. Higher ME together with lower protein content is typical for SSP1 rations. In contrast, in SSP5 proportionally higher protein contents are projected, which is related to the intensive use of protein-rich ingredients such as oil crops.

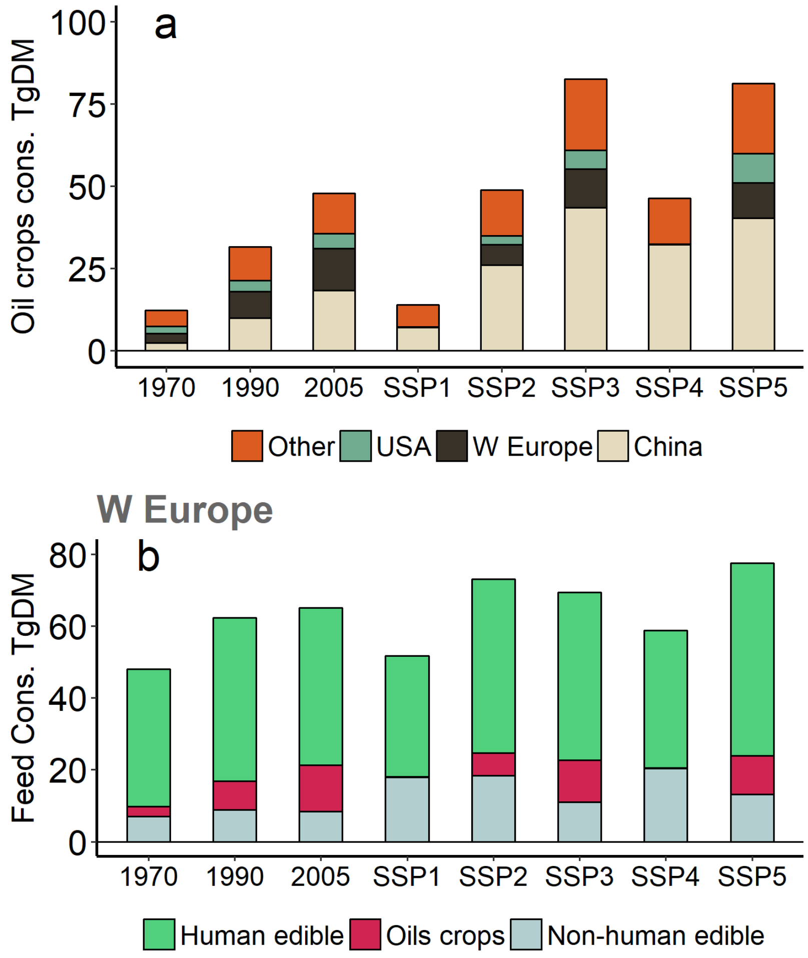

Fig. 5. Use of oil crops in some key regions, and use of non-human edible food in Western Europe.

The category of feedstuffs from household residues (swill) and by-products from the food industry accounted for a significant share of the total feed supply; from 33% in 1970 to 38% in 2005 (Fig. 6). In 2005, 77% of these residues were used for pig production in China (141 Tg DM), not only in backyard or intermediate systems but also in intensive systems (Bai et al. 2014). In intensive systems, and with the exception of China, household and industrial residues did not account for more than 5% in any region in 2005. This characteristic was maintained in all the SSPs, except for SSP1 where better processing and re-use of residues was projected (Fig. 5). The use of synthetic amino acids is generalized in all the SSPs except for SSP3.

3.3 Feed conversion ratios

The simulated amount of feed (expressed in kg DM) needed to produce 1 kg of carcass weight (feed conversion ratio, FCR) has steadily decreased (improved) for intensive systems over the last 35 years. The global weighted average FCR for all systems improved from 6.3 to 4.7 kg DM feed · kg product^{-1} (kg·kg^{-1}) (Fig. 6). In the backyard systems, the global FCR remains constant at 8.3 kg·kg^{-1} (range, 7.2–18.6 kg·kg^{-1} for 26 IMAGE regions) while in intermediate systems the FCR declined from 6.9 to 4.8 kg·kg^{-1} (4.2–9 kg·kg^{-1} for 26 world regions) and in intensive systems from 4.8 to 3.6 kg·kg^{-1} (3.5–4.4 kg·kg^{-1} for 26 world regions). The global total feed use was reduced by 25% because of these efficiency improvements during the last 35 years. In some regions, impacts are greater, for example, in Western Europe, where total feed use decreased by 35% due to FCR improvements in the 1970–2005 period.

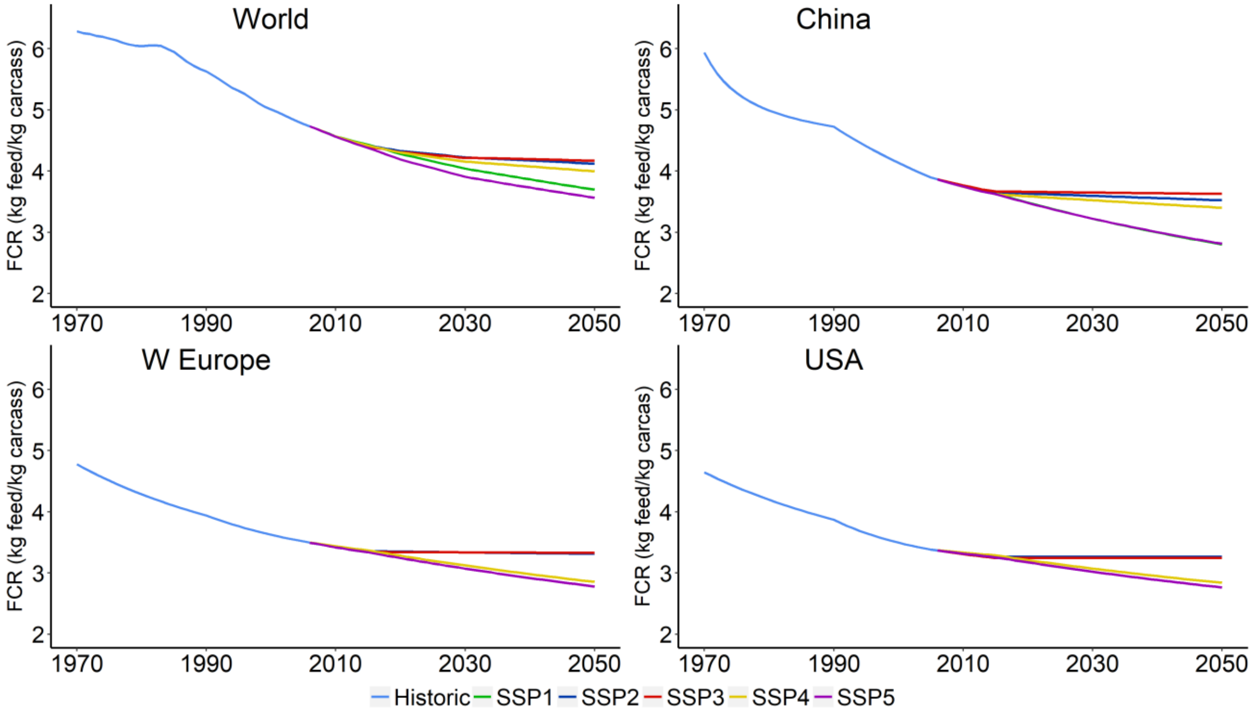

Fig. 6. Trajectories of conversion ratios (FCRs) aggregated for all systems at the global scale and for intensive systems in China, Western Europe and the USA for 1970–2050 for the five SSP scenarios.

With constant FCRs in SSP3 there is no increase, while in SSP1, SSP2 and SSP5 the declining FCRs will cause a major reduction of feed use (Fig. 6). FCR improvements lead to a reduction in total feed use that ranged from 94 to 160 Tg DM (for SSP2 and SSP5, respectively). The share of feed from alternative feed sources (including industrial and household residues, synthetic amino acids, brans, molasses and other residues) was 14% in 2005. This share is expected to increase rapidly, particularly in SSP1 where it is projected to increase to 35% of the total feed use.

3.4 N use efficiency and N excretion

The weighted average NUE at the herd level calculated by IMAGE-Pig (NUE, expressed as the percentage of the N supplied in the feed that is N retained in the carcass) of the world pig production systems only slightly increased from 14.8% in 1970 to 16.5% in 2005 (Fig. 7). Intensive systems have a better NUE in 2005 (23% world average) for some regions, but the increase over the last 35 years (1970–2005) estimated with IMAGE-Pig is moderate; the increase of NUE during the 1970–2005 period was only modest (Fig. 8), while the FCR was clearly improved (Fig. 6). This is due to the overall increasing use of protein-rich feedstuffs (Fig. 5). Improved rations with lower protein content will significantly increase NUE at similar FCRs in 2050. This is especially true for SSP1 for 2050 with NUE values of all the regions >30%, while in SSP5 NUEs are lower even with FCR values similar to those in SSP1 (Figs. 6–8).

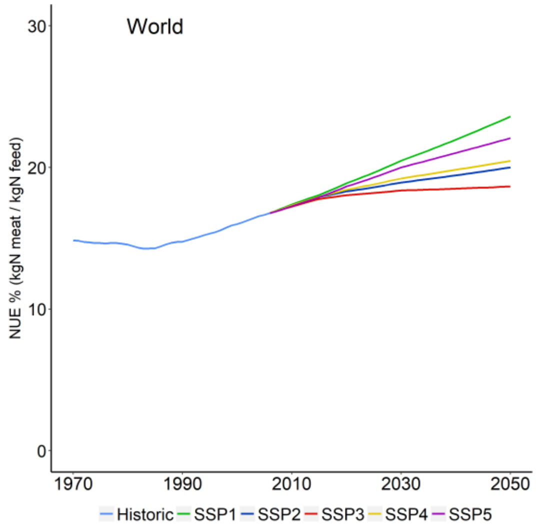

Fig. 7. Nitrogen use efficiency (NUE) at the herd level for all the systems (calculated as the percentage of N retained in the carcass per N input in the feed) for the historical and to 2050 for the five SSPs scenarios.

The estimated excretion rates are diverse. IMAGE-Pig predicted that the increase in the excretion rates of the intensive systems for most of the regions has been substantial over the last 35 years (see complete results in SM-1). For example, excretion rates in Western Europe in intensive systems increased from 6.9 in 1970 to 12.5 kg N/head/year in 2005 (at the herd level). Improved farm performance together with lower protein contents of rations in the SSP1 scenario lead to a decline of the excretion rates from to 8.5 kg N/head/year in 2050, while in SSP5 there is only a slight decline to 11.5 kg N/head/year. Total global N excretion by pigs increased from 4.6 Tg N in 1970 to 11.1 Tg N in 2005 (Fig. 9). In 2005 50% of global pig N excretion was concentrated in the China region. The projected global excretion in SSP1 for 2050 is 8.6 Tg N, which is a decline from 2005 despite the global production increase. This decline of excretion is not projected in the other SSPs. The highest excretion by pigs in 2050 is projected for SSP3 (16.5 Tg N/year) and SSP5 (15.8 Tg N/year).

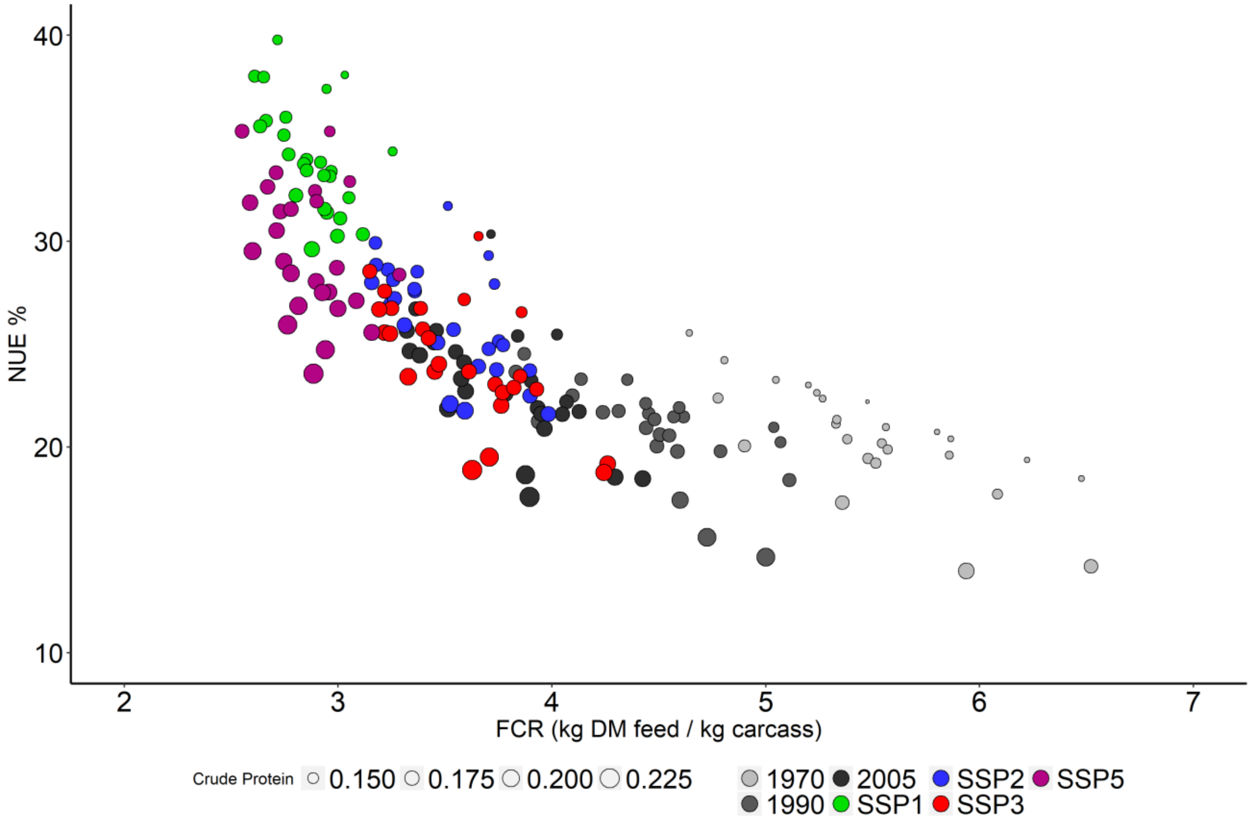

Fig. 8. The relationship between the feed conversion ratio (FCR) and nitrogen use efficiency (NUE) for the 26 IMAGE regions for intensive systems for 1970, 1990, 2005 and 2050 for the five SSP scenarios. The size of the dots indicates the crude protein content of the ration (percentage of DM).

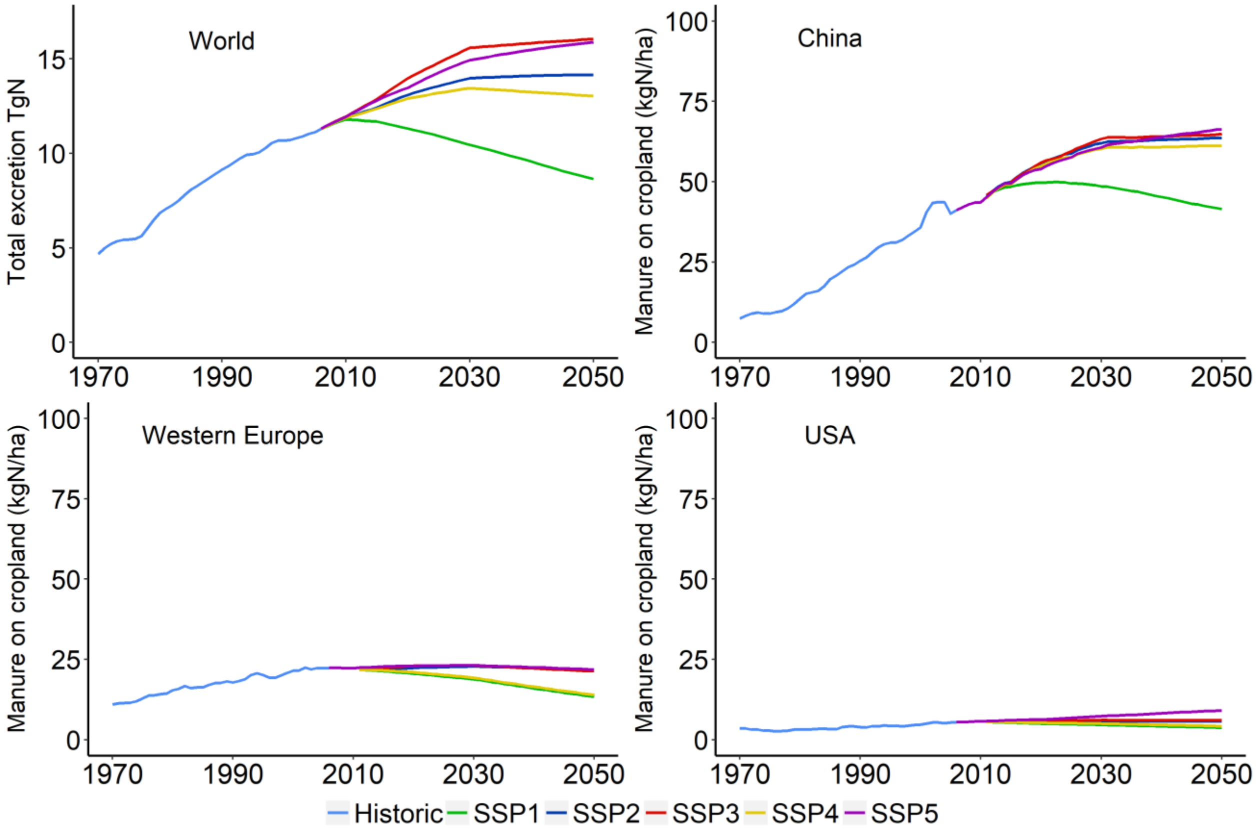

Fig. 9. Scenario-specific total N excreted in pig production systems and uniform distribution over the regional croplands; 25% of ammonia has been discounted assuming volatilization in pig housing and manure storage.

Only in the SSP1 scenario do we see a decline in the global amount of N from pig excretion (Fig. 9). To evaluate the magnitude of the challenge for sustainable manure management, we estimated the amount of N available used as fertilizer in the hypothetical case that it is evenly spread on croplands. The total excretion was corrected subtracting 25% ammonia losses due to volatilization in animal houses and storage systems. The available N for spreading on croplands in Western Europe has increased twofold from 11 kg N/ha/year in 1970 to 22 kg N/ha/year in 2005. Using the cropland areas projected by the IMAGE model, in SSP1 the available manure N in Western Europe will decline to 13 kg N/ha/year in 2050, while in the other scenarios it will stabilize after 2005. The pig manure availability for spreading in croplands in other world regions is small compared to that in Europe (Fig. 9). In the case of China, there is a much greater potential for recycling pig manure. In 2005 there is 40 kg N/ha/year in pig manure available for spreading in Chinese croplands, accounting for a six-fold increase compared to 1970 values

(Fig. 9). IMAGE-Pig projects a slight decline to 46.9 kg N/ha/year for SSP1 when compared to the current situation and larger increases for the other SSP scenarios (approx. 60 kgN/ha/year).

3.5 Validation and sensitivity analysis

The Nash-Sutcliffe model efficiency (values always exceeding 0.9) indicates good agreement between the pig stocks simulated with IMAGE-Pig and those from FAOSTAT for the 1990–2015 period (Fig. 10). For the 1980–1990 period the model efficiency is satisfactory (>0.75). Prediction levels for the 1970–1980 period are lower but still acceptable (range, 0.56–0.7).

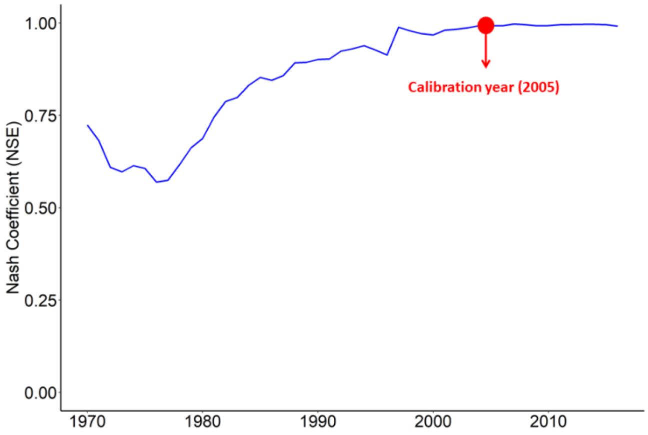

Fig. 10. Nash–Sutcliffe model efficiency for comparison of pig stocks from IMAGE-Pig predictions and FAOSTAT estimates for the 1970–2016 period, every year *n*=26 IMAGE regions.

The model sensitivity analysis using Latin Hypercube Sampling (LHS) revealed that the inputs associated with production (AGRPRODAN, and CW), together with the distribution of production over the three systems (FRPROD), are the most important parameters determining the main outputs such as feed demand, excretion and stocks (see SM-1). ADG is the next most influential input. We performed a second sensitivity analysis maintaining AGRPRODAN, FRPROD, and Carcass Yield constant at each region in order to explore the sensitivity of the model to specific productivity parameters within each system. In this case again ADG proved to be important, as well as the parameter litters/sow/year. Litter size is less important, but its influence on FCR values is considerable in some regions (see SM-3).

4. Discussion

The IMAGE-Pig module calculates feed demand, feed efficiency and N excretion of global pig production systems for 26 regions and three systems. The results are within the range of other global and regional estimations. The model estimates of pig stocks for the 1985–2015 historical period are in good agreement with the statistics. IMAGE-Pig compares well with a number of studies from the literature for a range of outputs. The production per system as estimated by IMAGE-Pig at the global scale (19% backyard, 24% intermediate and 57% intensive) agrees with findings of Macleod et al. (2013) (21%, 19% and 60%, respectively) for the year 2005. The IMAGE-Pig result for feed consumption for 2000 and 2010 (451 and 506 Tg DM, respectively) is lower, but within the range of global estimates by Herrero et al. (2013) (537 Tg DM for 2000) and Mottet et al. (2017) (556 Tg DM for 2010). The model FCRs at the global scale for the year 2005 (8.3, 4.3 and 3.6 for backyard, intermediate and intensive systems, respectively) are similar to those estimated by Macleod et al. (2013) (median FCRs, 8.2, 4.5, 3.6 kg kg^{-1}, respectively). The regional results of IMAGE-Pig for Western Europe (3.4 kg kg^{-1} in 2010 for intensive), the USA (3.4 in kg kg^{-1} in 2005 for intensive) and China (5.0 in 2010 for all the systems) are also consistent with other regional averages provided in other studies, namely 3.8 kg kg^{-1} in the EU 27 for intensive systems in 2010 (Huo et al. 2016), 3.6 kg kg^{-1} in the USA for intensive systems in 2005 (Peters et al. 2014) and 5.0 kg kg^{-1} in China for all the systems in 2005 (Bai et al. 2014). Macleod et al. (2013) provide a range of NUE values of 14–18%, 20–25% and 22–35% NUE for backyard, intermediate and intensive systems in 2005, respectively, where IMAGE-Pig estimates 7–18%, 13-24% and 23–40% (expressed as N in the live weight per N intake). Bai et al. (2014) estimated NUE at the herd level (also expressed as N retained in live weight per N input) for the total Chinese pig production system to increase from 18% to 19%, 23% and 21% for 1970, 1990, 2000 and 2010, respectively. This finding is similar to IMAGE-Pig estimates of 16%, 18%, 19% and 21% for 1970, 1990, 2000 and 2010, respectively. Total excretion values agree with Sheldrik et al. (2003) estimations of 10.4 TgN in 1996 (10.1 TgN by IMAGE-Pig). Excretion rates are also within the range of the average EU-28 values (Pierer et al. 2016). Thus, IMAGE-Pig demonstrates that it is a useful tool in itself to evaluate the global and regional environmental impacts of pig production systems. Moreover, given the large implications of the pig sector in terms of land use and emissions, a good representation in the IMAGE framework of this sector is crucial as a relevant component of agro-food systems.

The results show that today the influence of pig production on the global agro-food system is very important due to the large amount of human edible crops used as feed, as well as the large amount of nutrients excreted by animals in manure. The demand for food crops for feed is expected to persist and to increase in the coming decades, particularly in China, Europe, and the USA, but also in South America and Southeast Asia. The expected increase in the feed demand in most of the scenarios will increase the competition for land (Doelman et al. 2018), potentially contributing to land grabbing problems (Suweis et al. 2016) as well as the growth of deforestation. The increase in the use of new fertilizers for producing feed (Mogollon et al. 2018) would also produce more emissions of reactive nitrogen compounds at the cropping system level (Garnier et al. 2019). These problems would be exacerbated if the increase in crop yields per hectare stagnates (Grassinni et al. 2013).

Current developments in science and policy to design future sustainable agro-food systems require a deep understanding of the functioning and potential development of the pig production sector. In 2005, feed demand (expressed as DM) was equivalent to 14% of crop production considering that a large part of the feed has a direct or indirect origin in crop production (feed crops and household and food industry residues) (Table 2). While the total feed demand will increase in all the scenarios between now and 2050 (with the exception of SSP1), the proportion of feed to the total crop production is projected to decrease by 11–12% due to significant increases in crop production estimated for each SSP scenario by the IMAGE model (van Vuuren et al. 2017; Doelman et al. 2018). If expressed as N the share is higher, since in 2005 pig feed contained 15 Tg N, which is equivalent to 19% N in harvested crops (directly used or as swill or food industry residues). This figure is consistent with the top-down estimate by Lassaletta et al. (2016).

IMAGE-Pig results show how increases of FCR have consistently reduced feed demand per unit of pork in past decades. Between 1970 and 2005, the increase in efficiency has reduced the global amount of feed by 178 Tg of DM, which is 37% of the feed use in 2005. However, the improvements resulting in a higher FCR were not sufficient to compensate the increase in global pork production and the associated increase in global feed demand (Bai et al. 2014; Davis et al. 2015; Lassaletta et al. 2016). Due to the rapid changes in technology and management in the pig sector (e.g. the precision livestock farming, Tullo et al. 2019), further FCR increases during the coming decades can result in lower feed demand per kg of product, as demonstrated in SSP1 and SSP5. These improvements are slightly lower than those estimated for the previous decades because pork production is approaching zootechnical potential production limits, and because of increasing limits due to the animal welfare requirements of biological limitations (e.g., biological limit of 2.5 litters/sow/year). Therefore, efficiency improvements are leveling off and they may not be sufficient to reduce the pressure on the global agro-food system induced by the increasing global demand for pork (Davis et al. 2017). Only in SSP1 there is a slight reduction of the feed demand expected by 2050, which is associated with moderation of human meat consumption together with efficiency improvements in production. The principles of this storyline are comparable to the sustainable scenario proposed by Springmann et al. (2018) seeking to avoid trespassing the planetary boundaries by 2050.

Direct consumption of maize and oil crops (most in the form of soybean meal) by pig systems accounted for 12% of global maize and 25% of global soybean production in 2005 (FAO, 2017). Feed demand is projected to double between now and 2050 in the SSP3 and SSP5 scenarios. This projected increase is a concern because, since 1995, the increasing feed demand has led to environmental impacts in feed-exporting countries (Lassaletta et al. 2014b; Oita et al. 2016) such as deforestation, biodiversity loss and water and air pollution: deforestation and forest degradation resulting from expanding soybean production in South America (Leip et al. 2015; Caro et al. 2018), or air and water pollution in soybean-corn production areas in the USA (Paulot and Jacob, 2013). For pig-producing countries relying on imported feed, the geographical concentration of pig production faces limitations to spreading and efficient use of manures in nearby cropping systems (Billen et al. 2018; Wang et al. 2018) due to the high costs of manure transport and application in other regions (Willems et al. 2018; van Grinsven et al. 2018). As a result, manure is in many cases applied locally at rates that exceed crop needs, such as in certain areas of Spain (Peñuelas et al. 2009; Lassaletta et al. 2012), France (Le Noé et al. 2017) and the Netherlands (Willems et al. 2016). Manure may even be directly discharged to water bodies, as in some areas of China (Gu et al. 2015; Liu et al. 2018).

Pig N excretion was equivalent to 18% of the synthetic N fertilizer used in the agricultural sector in 2005 (92.9 Tg N, IFADATA). Overapplication of manure to crops, however, causes disproportional air and water pollution, also causing a decrease in NUE at the overall crop-livestock system level (Bai et al. 2014). Our scenario results indicate that in 2050 a considerable amount – 8.6 to 16.5 Tg N/year – will have to be properly managed to utilize the fertilizer potential, while avoiding environmental problems. The development of more integrated spatial outlays of feed-livestock systems therefore is an important strategy in the upcoming decades to boost nutrient recycling and improve sustainability of pig systems (van Grinsven et al. 2015; Garnier et al. 2016; Garret et al. 2017; Liu et al. 2017; Billen et al. 2019). How to configure territories reconnecting crops and livestock systems to improve system efficiency is a relevant object of research that involves a high level of governance and the contribution of all stakeholders (Billen et al. 2019; van Grinsven et al. 2018).

The contrast between SSP1 and SSP5 in 2050, with a similar FCR but very different NUEs, shows how important balanced rations with reduced crude protein content are in reducing total N excretion and increasing herd NUE. Furthermore, the projected widespread increase of alternative feedstuffs not competing with human food (in terms of land or products) will reduce the global demand for feed crops. Using swill in industrial systems would have reduced land requirements by 20 million ha in 2010, of which 90% corresponded to soybean (Uwiyeze et al. 2018). As shown in SSP1, more than 30% of the ration could come from alternative feed sources, but it will be a challenge to use the full potential of residues from the food industry, retail and processed food wastes. Zu Ergmassen et al. (2016) estimated that in Europe 11 Tg DM of food waste could be recycled as feed in 2015 (namely, 4.5, 0.5, 1.2 and 4.2 from manufacturing, retail, catering and household wastes, respectively). In SSP1 a demand of 8.4 Tg DM of alternative feeds is estimated in Western Europe, indicating that this transition is feasible. Finding alternative sources of protein has become an urgent objective, because of biodiversity loss caused by expanding soybean production in feedstuff-producing countries. Apart from ongoing projects to develop recycled sources of protein, it may be expected that ambitions for a circular economy and bio-based industries will enhance protein recycling in the near future.

The reduction of per capita demand for pork, as considered in several regions in the SSP1 scenario, is the most effective way to reduce the environmental impacts of feed and pork production. Transitions of the agro-food system should consider not only supply-side solutions at the farm and crop-livestock system level, but also demand-side changes, necessary to achieve sustainability (Westhoek et al. 2014; Billen et al. 2015; Bodirsky et al. 2015; Lamb et al. 2017; Springman et al. 2018). For example, Frank et al. (2018) estimated that in 2050 equivalent amounts of greenhouse gas mitigation potential of the agro-food system can come from technological, structural and consumption measures. This conclusion agrees with our findings for pig systems in SSP5, where in spite of efficiency increases, the projected increase in pork production will lead to increasing feed use and N excretion (structural changes including recirculation and re-use of alternative feeds), while the consumption transitions assumed in SSP1 will lead to more sustainable production. Finally, we acknowledge that we did not account for several important aspects, such as the future demand for increased animal welfare, the effect of crop and livestock disconnection, the effect of climate change, barriers to change and the influence of poultry production (IMAGE-Poultry, in prep.) and other non-food sectors such as biofuels. These aspects will be considered in future modeling efforts.

Conclusions

The general improvement of feed conversion efficiency (FCR) in pig production systems from 1970 to 2005 has significantly reduced feed consumption per kg of carcass. However, the significant increase in the pork demand caused steady growth of >100% of the global feed consumption during that period. By 2050, only in the “green growth paradigm” scenario (SSP1) including measures on both the supply (farm performance and improved rations) and demand sides (moderate diets), the global feed demand is projected to stagnate. In SSP5, also with improved FCR, a substantial rise in the pork demand could increase the demand for feed by approximately 50%. The total N excretion almost tripled in the 1970–2005 period. FCR improvements could not counteract the increase of pork production and the change in feed ration composition with more crude protein. By 2050, the excretion could rise 50% in SSP5, whereas it is projected to be reduced in SSP1. The use of alternative feeds in combination with lower crude protein contents through improved feeding strategies and genetics are essential to decrease feed/food competition and reduce N excretion, while increasing NUE. Apart from structural and technological changes, human diets play a crucial role in determining total pork production, feed use and N losses to the environment associated with feed and pork production and manure management. Thus, the sustainability of pig production systems for the coming decades will rely not only on the expected efficiency improvements at the herd level, but also on four additional pillars: an increased use of alternative feed sources, reduced crude protein content in the rations, the proper use of pig manure as fertilizer through crop-livestock reconnection, and finally the moderation of the human demand for pork.

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Table 1. Scenario-specific characteristics used for the IMAGE SSPs implementation for 2050

	Region*	**1970**	**1990**	**2005**	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
Key word					Sustainability	Middle of the Road	Fragmentation	Inequality	Fossil fuel
Per capita demand					Low	Medium	Function of GDP	Function of GDP	High
Technological development					Rapid	Medium	Slow	Slow	Rapid
Crop and livestock efficiency					High	Medium	Slow	Unequal	High
Progress towards development goals					Good	Some	Failure	Highly unequal	Market-driven
Environmental awareness					High	Medium	Low	Unequal	Low
Resource intensity					Low	Medium	None	Highly unequal	High
Population (million inhabitants)	World	3776	5308	6531	8531	9243	10038	9213	8629
	Industrialized	826	936	1016	1221	1191	1011	1123	1383
	BRIC	1667	2347	2821	3162	3408	3708	3166	3165
	Rest of world	1284	2026	2694	4147	4644	5319	4924	4081
GDP/capita (US$)	World	4254	5703	6967	24563	17877	12024	17500	32449
	Industrialized	16010	25383	32885	60131	55180	50917	62996	70986
	BRIC	623	1148	1938	25577	16765	10413	17474	34063
	Rest of world	1405	1890	2456	13318	9130	5752	7139	18138
Pork production (Mt)	World	39	70	99	125	160	165	153	207
	Industrialized	23	32	36	35	44	43	42	59
	BRIC	11	30	51	69	93	95	89	119
	Rest of world	5	8	12	20	24	27	22	29

* Industrialized includes Canada, the USA, Western and Eastern Europe, Japan and Oceania; BRIC: China, India, Russia and Brazil.

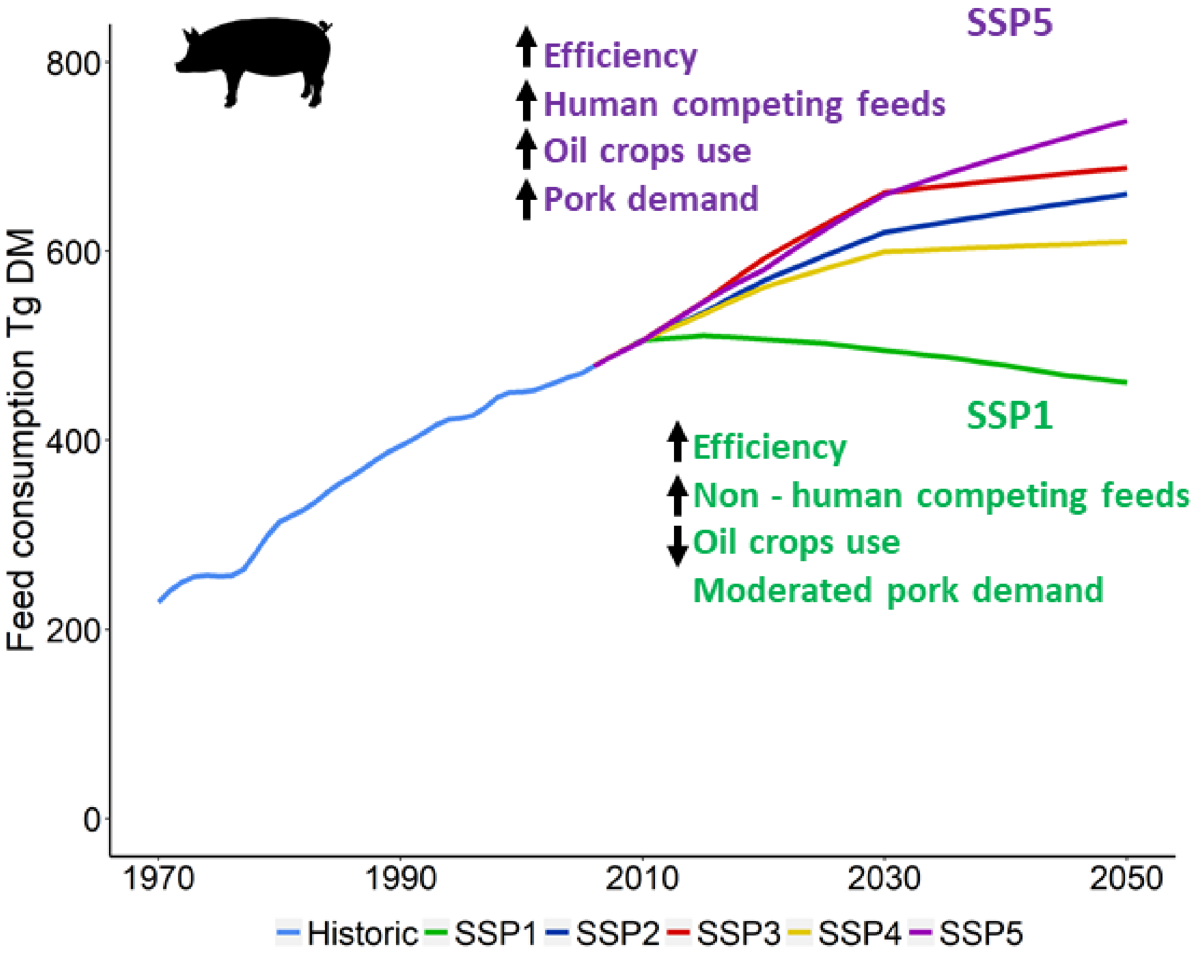
Table 2 Feed use for 15 feedstuffs, total energy and protein content, protein/energy ratio of global and intensive pig production systems and total crop production for 1970, 1990, 2005 and for 2050 for the five SSPs.

Feed stuff (Tg DM)	**1970**	**1990**	**2005**	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
temperate cereals	50	69	57	51	79	81	63	80
rice	0	3	3	8	11	12	9	12
maize	37	46	78	97	140	140	133	159
tropical cereals	5	7	4	10	12	10	8	8
pulses	2	2	2	3	3	2	3	4
roots and tubers	8	18	17	22	26	19	30	37
oil crops	12	32	48	14	49	83	46	81
animal source	2	3	2	5	7	7	6	7
brans	18	31	41	54	68	60	65	56
DDGS	0	0	3	4	5	5	6	12
molasses	1	2	2	6	6	2	4	6
swill, industrial/household residues	82	155	184	156	215	232	197	228
synthetic	0	4	5	10	13	10	13	14
other residues	13	23	24	22	26	25	27	33
Total demand (Tg DM)	229	394	471	461	660	688	610	738
Protein (Tg N)	6	12	15	13	20	22	19	23
Total ME (PJ)	2966	5000	6010	6702	8636	9028	7966	10744
ME/kg DM (intensive)[2]	15.0	14.7	14.5	15.8	14.1	14.2	14.7	15.9
ME/kg DM (intermediate)	12.8	12.5	12.0	12.1	12.0	12.0	12.0	12.0
ME/kg DM (backyard)	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
% CP/kg DM (intensive)	14.1	17.9	19.9	16.6	18.6	20.5	18.8	20.1
% CP/kg DM (intermediate)	16.8	19.1	19.6	19.5	19.6	19.6	19.6	19.6
% CP/kg DM (backyard)	19.6	19.6	19.6	19.7	19.6	19.6	19.6	19.6
Total crop production Tg DM	1644	2594	3390	5555	5985	6180	5716	6418
Total crop production Tg N	33	57	83	136	148	152	138	157

[1] World weighted average of regional rations.

CP, crude protein; DDGS, distiller's dried grains with solubles; DM, dry matter; ME, metabolizable energy; PJ, Petajoules.

Graphical abstract



Highlights

- IMAGE-Pig model describes the functioning of pig production systems in 26 regions
- Feed demand, feed efficiencies, and excretion are estimated (1970-2050)
- Total feed use increased, as past efficiency improvements grew slower than demand
- SSP1 shows a more sustainable path, with reduced meat demand and efficiency gains
- By 2050 feed use and environmental impacts can be strongly reduced or increased