Modelling nitrogen use efficiency by world pig production systems in 2050 under contrasting production and dietary scenarios

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Abstract
In this study we model the global feed and land demand, nitrogen excretion and nitrogen use efficiency (NUE) for pig production systems in 2050 under different scenarios for pork demand, production performance and dietary composition. We developed a new pig module for the IMAGE integrated assessment model and we constructed a set of scenarios following the storylines of the Shared Socio-economic Pathways. Our model outcomes suggest that pig production systems will play a significant role in the global agro-food system in 2050 including protein supply, land demand and N fertilization. The sustainability of future pig production systems will strongly depend on the livestock production performances, feed rations and manure recycling efficiency. Scenario analysis suggest that the replacement of part of the soybeans by swill and industrial by-products in the feed ration of pigs is a promising solution to increase NUE as well as to reduce the land demand associated with pork production.

Key Words
Feed, pig production systems, N excretion, nitrogen use efficiency, ration, Shared Socio-economic Pathways

Introduction

Pig production accounted for 37% of total livestock production in 2012 (111 Tg of pig meat expressed in carcass weight, CW) and total production is expected to increase by 2050 (Alexandratos and Bruinsma 2012). Pigs are fed large amounts of cultivated feed that could also be part of the human diet. More than 75% of the nitrogen (N) in feed proteins is excreted and this can cause severe environmental problems if not properly managed (Lassaletta et al. 2016). Pork is produced in a variety of production systems with different levels of market orientation, performance and dietary requirements, and that significantly affects the local and global demand of feed as well as the NUE. With the growing share in total meat production, pig production will therefore play an important role in the global agro-food system during the next decades, as a food resource, feed consumer and manure producer.

A new set of scenarios called the Shared Socio-economic Pathways (SSPs) has been developed describing several possible future development trajectories. Some of these SSPs have been recently implemented in the IMAGE 3.0 integrated assessment model (Stehfest et al. 2014). The SSP1 storyline describes an efficient world with economic prosperity, technological progress and societal environmental concern. SSP2 corresponds to the "business as usual" expected trajectory. The IMAGE pigs module has been recently improved including the description of the functioning of backyard, intermediate and intensive production systems and detailed information on herd and nutritional needs and use for the 26 world regions considered by the model.

This modelling study explores the feed and land demand, the N excreted and the NUE (at the herd level) in 2050 (base year for SSPs scenario construction) by world pig production systems under different scenarios for pork demand, production performance and feed ration.

Methods

The new pigs sub-model implemented in IMAGE consists of four modules: 1) Meat production; 2) Herd composition; 3) Energy requirement; 4) Nitrogen budget. *The Meat production module* estimates the amount of meat produced by system (backyard, intermediate and intensive) and IMAGE region (26 world regions). *The Herd module* estimates the number of heads by system and region and the off-take rates for 11 different cohorts (including boars, gilts, sows and fatteners pigs at different stages), transfer between cohorts, replacement and mortality. *The Energy module* estimates the energy and dry matter (DM) needs, and the feed conversion ratio. This module calculates the energy need for each animal cohort according to its physiological state and needs following NRC (2012) recommendations (including energy needs for lactation, pregnancy, growth and maintenance). *The Nitrogen budget module* estimates the protein needs, N use efficiency and excretion. This module estimates the N retained (considering growth, milk and pregnancy), the total N input in the ration by cohort. Feed is supplied to meet the energetic needs, accounting for a minimum amount of protein requirement. In total 20 parameters have been estimated for each system and IMAGE region. The pigs sub-model requires data on: 1) Pig meat production by IMAGE regions (source: FAO); 2) Distribution of pig production over backyard, intermediate and intensive systems (source: Robinson et al. 2014); 3) Herd and performance variables including several parameters on herd structure, mortality, reproductive traits and growth rates (source: modified from amongst others Macleod et al. 2013); 4) Diet composition including energy, dry matter and protein content of each ration (Source: various). Data on number of heads per production system and region are only available for 2005. Therefore 2005 was used for model calibration, which resulted in a good agreement (RSME = 0.15).

In 2005 global pig production expressed in CW was 96 Tg, 19% produced in backyard, 11% in intermediate and 70% in intensive systems. The feed rations, specific at the regional and system level, were estimated for the 26 IMAGE regions based on Macleod et al. (2013) and other literature. Three scenarios for 2050 were constructed using the same feed rations for each pig production system as in 2005 but with different production performances: ***SSP2*** (168 Tg CW with the same production performances as in 2005), ***SSP1*** (151 Tg CW and improved fatteners daily weight gain, litter size and number of litters per sow per year), ***SSP2+*** (168 Tg CW and same production performances as SSP1). Improved performances have been based on current knowledge on biological and technical-economical limits for pig production. Thus, all regions were considered to converge towards productive levels of countries with high productive pig production systems (e.g. USA or Western Europe).

A second set of scenarios was constructed to evaluate the effect of ration on feed and land demand, NUE and excretion by using the same parameters as in *SSP2+*, but with a modified ration (***SSP2+D1***, ***SSP2+D2***, ***SSP2+D3***, Table 1). The three rations are common in current pig production systems with large shares of cereals (D1), soybean co-products (D2) or industrial by-products and swill (D3). The productivity (tonnes/ha) estimated by Alexandratos and Bruisma (2012) for these feed commodities for 2050 was used to calculate the land required to produce the feed under the scenarios *SSP2+D1*, *SSP2+D2* and *SSP2+D3*.

Table 1. Composition and nutritional values of the rations used in scenarios *SSP2+D1*, *SSP2+D2* and *SSP2+D3*

		SSP2+D1	*SSP2+D2*	*SSP2+D3*
	Feedstuff	Cereal	Soybean	By-products
Ration (% of each feedstuff)	Maize and products (%)	0	56	18
	Barley and products (%)	44	0	7
	Brans (%)	0	12	25
	Wheat and products (%)	45	0	30
	Swill (%)	0	0	10
	Molasses (%)	0	0	10
	Soybean Cake (%)	11	32	0
Nutritional values	Feed metabolizable energy (MJ/kg of DM)	14.9	15.1	13.4
	Crude protein feed (%) DM	16.2%	23.8%	13.1%
	N content (%) DM	2.6%	3.8%	2.1%

Note: Rations for SSP1, SSP2 and SSP2+ are based on literature and are different for each region and system

Results and discussion

The model results estimate that 424 Tg of DM and 12 TgN were used in global pork production systems in 2005. This amount of N represented 17% of the total protein produced in the world cropping systems in 2005 (Lassaletta et al. 2016). The NUE calculated at the herd level (as the percentage of N of the feed retained in the CW) ranged from 7% to 25%. The lowest NUEs (< 10%) are estimated backyard systems where the reproductive and fattening performances are particularly low (e.g. African regions). The highest NUEs are in intensive systems in China, Europe and USA. China uses 50% of world's feed production allocated to pigs, and Europe (15%) and USA (7%) much less. The excretion ranged from 7 to 19 kg N/head/yr, and the rates are in good agreement with literature values (e.g. 10, 11 and 14 kgN/head/y for China, USA and Western Europe, respectively). The modelled estimate of global N excreted by pigs is 10.8 Tg N for 2005, which agrees with the 10.6 Tg N estimated by Lassaletta et al. (2014) based on dynamic excretion factors based on CW productivities. This amount equals 10% of the total N excreted by world livestock systems and 12% of the synthetic N fertilizer use in 2005and therefore it represents an unneglectable amount of N to be reused.

Depending on several factors, this N excretion can be both a valuable source of N fertilizer or produce severe environmental problems. The N excreted in backyard systems is 37% of the total excretion, which exceeds their contribution to total CW production (20%) due to lower efficiencies and rations. However, backyard pig production systems can be a valuable source of fertilizers in the cases they are based on a close coupling of crop and animal production by exchanges of crop (by) products and manure and with less spatial concentration than some intensive pigs production systems. For example, the transition from backyard to more intensive pig production systems was associated with a shift towards concentration of pork production in confined feeding operations requiring large feed imports; this decoupling of feed and meat production also led to direct discharge of pig slurry to surface water (Strokal et al. 2016), and to low NUE at the system level (Bai et al. 2014). The degree of recycling of the manure N in cropping systems is determined by environmental regulation and economic incentives (Van Grinsven et al. 2015).

In 2050 with the current performances but with the pork production estimated in *SSP2*, the total feed DM demand is predicted to increase by *ca*. 100% (823 Tg DM), while for *SSP1* it increases by 50% (672 Tg DM) compared to 2005 (Figure 1a). A general efficiency improvement would reduce the DM demand by 10% in *SSP2+* (741 Tg DM). A global transition to rations with higher nutritional value by increasing the share of cereals and soybeans would reduce the feed DM demand by another 10% (657 and 649 Tg DM for *SSP2+D1* and *SSP2+D2*, respectively). The DM demand and excretion from the soybean diet scenario SSP2+D2 is similar to that of the SSP2+ scenario that assumes no change in feed rations (MacLeod et al. 2013).

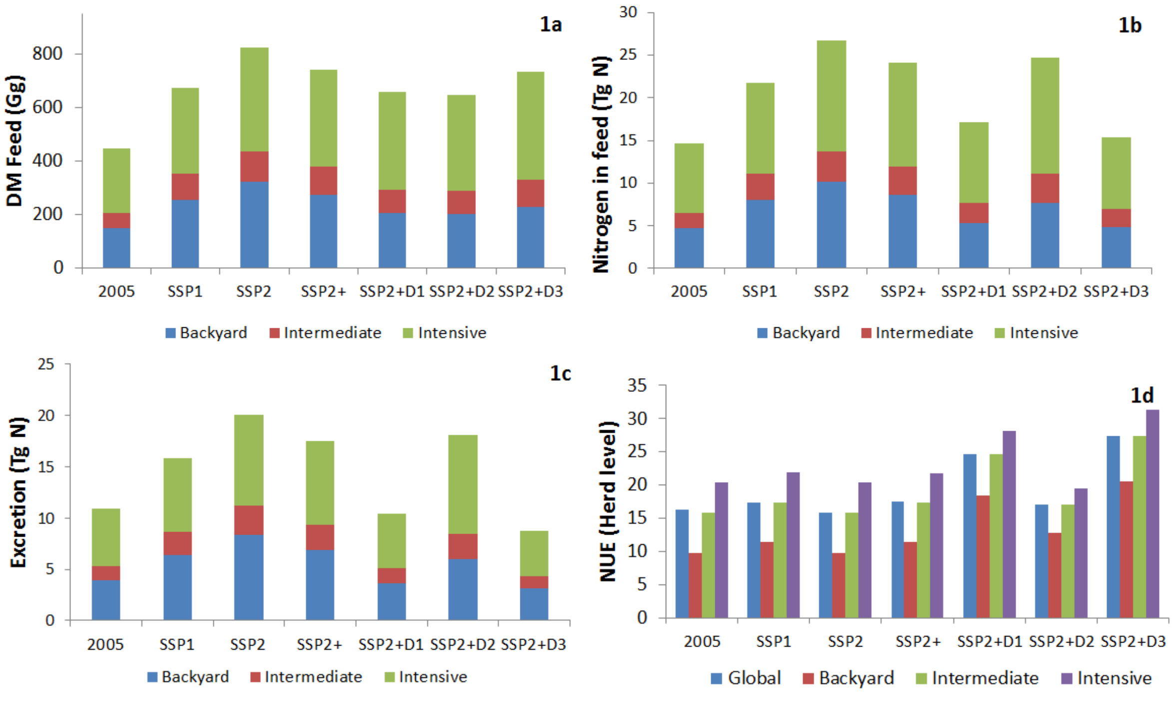

Figure 1. Predicted total dry matter (DM) (a) and N content (b) of the feed (calculated based on feed demand and rations composition), N excretion (c) and herd level Nitrogen Use Efficiency (NUE) (d) of the world pig production systems in 2050 under different production and dietary conditions.

The total N in the feed is significantly different for the studied scenarios (Figure 1b). In the Soybean scenario *SSP2+D2* (also similar to SSP2+ based on current diets), 25 TgN is embedded in the feed, compared to only 17 TgN in the Cereals (*SSP2+D1*) and 15 Tg N in the By-products scenario (*SSP2+D3*) (the model provides enough feed to meet energy demand and in all cases the protein supply largely exceeds the protein needs of the animals). This amount would account for 15% to 25% of the total world protein production in croplands estimated by Lassaletta et al. (2016) for 2050. Both efficiency and ration have an important effect on the total N excretion (Figure 1c). The predicted global N excretion almost doubles in *SSP2* (20 TgN) compared to 2005, due to high pork demand and production with no change in rations and performances. The three alternative rations represent a generalized global diet for pig livestock systems and they are meant to be exploratory and not prescriptive. These scenarios all lead to lower global N excretion but with large differences between them. The total excretion estimated for the Soybean diet *SSP2+D2* is 10% lower than in SSP2 (17.5 TgN). The global excretion in 2050 is even lower than in 2005 (10.8 TgN) in the Cereals (*SSP2+D1*10.4 Tg N) and by-products scenario (SSP2+D38.8 Tg N). In *SSP1*, *SSP2*, *SSP2+* and *SSP2+D2*, global NUE for 2050 was comparable to 2005 (about 17%), while for the *SSP2+D1* and *SSP2+D3*, NUE increases to 25% and 27%, respectively. The low NUE and high excretion obtained in the *SSP2+D2* is associated with the lower energy/protein ratios.

In contrast, concerning land demand, the situation is reversed. The land requirement for feed production in *SSP2+D2* is less (166 Mha including 80% of expected global soy production estimated by Alexandratos and Bruinsma, 2012) than in *SSP2+D1* (238 Mha). In the case of the by-products scenario *SSP2+D3*, the estimation of the land demand for feed production depends on how land is attributed to products. For swill the land cost can be considered to be negligible, whereas for many by-products most of the land use is usually allocated to the main product (e.g. wheat flour for wheat). Therefore, the land demand is lowest in the By-products scenario *SSP2+D3* (112 Mha). This confirms a recent study by zu Ermgassen et al. (2016) who highlighted that a significant amount of land could be saved when including swill in pig rations, without affecting the quality of the pork.

Conclusions

The expected increase of global pig production in 2050 is predicted to lead to an increase of feed and land demand. The sustainability of pig production systems has several dimensions, and depends, amongst others, on the reproductive and fattening performances and rations. Depending on the feed ration, between 15% and 25% of the protein that is expected to be produced in the world cropping systems in 2050 would have to be allocated to pig production systems. A transition to pig feed rations richer in soybean cakes in 2050 would result in a fast increase in soybean production worldwide, a drop in the NUE, an increase of global N excretion and a lower land demand when compared to cereal based diets. The inclusion of swill and by-products in the rations has the potential to reduce land demand. Despite the estimated generalized increase of NUE at the herd level, if the excreted N is not properly recycled in cropping systems the NUE at the system level could decline.

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