A bio-economic analysis of a sustainable agricultural transition using green biorefinery

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A bio-economic analysis of transition to bio-based agriculture based on green biorefinery

Abstract:

Traditional pig production often highly relies on the cereal-based feed, which has adverse effects on the environment, e.g. unsustainable carbon and nutrient flux with cereals production. A promising alternative is to use proteinaceous feed from grass, which is produced at the green bio-refinery (GBR), to substitute part of the cereals. Cultivation of grass on arable land can reduce nitrogen leaching and pesiticide application. The GBR using grass as feedstock also produces valuable byproducts, e.g. fiber and biogas. The residues from production at GBR can also be fed back to the land as fertilizer with reduced environmental effects. In this study we will use the life cycle analysis (LCA) to analyze the economic and environmental effects of pig feed for producing one ton pork with two feeding systems. The results show that compared with traditional cereal-based feeding system, for producing one ton pork (1) the average feed cost will decrease by 5.01%; (2) the GBR will produce a profit of 96 € before tax; (3) the nitrate leaching (NO_3-N) will decrease by 26.8% with the alternative feeding system. However, in most of the scenarios (except for G2), the nitrogen emissions into the air will also increase because of the increased N fertilizer applied to the grass production, e.g. N_2O-N and NO_x-N will increase by 8.84% and 8.72%, respectively in the reference scenario. In most of the scenarios (except for S1 and G1), the energy and land use will also be saved. However, some important factors, e.g. the soil condition and pressed juice fraction in fresh biomass, could subvert the conclusion about energy and land use saving with the alternative feeding system.

Keywords:

Biotechnology; Cost-benefit analysis; Greenhouse gas emissions; Nitrogen leaching; Proteinaceous feed; Sustainable agriculture

Nomenclature

AT	Advanced Technology	LCA	Life cycle analysis
BT	Basic Technology	LV	Low volume
DM	Dry matter	MJ	Megajoules
FCR	Feed conversion ratio	MV	Medium volume
FM	Fresh matter	N	Nitrogen
GBR	Green biorefinery	P	Phosphorus
GHG	Greenhouse gas	PJ	Press juice
GS	Grass/silage as feedstock	PC	Press cake
HV	High volume	S	Using only silage as feedstock
IO	Input-output	WOI	Weaning-to-oestrus interval

1. Introduction

Nowadays, the Danish pig industry mainly depends on the local cereal-based fodder and imported soya. However, when growing such cereals there are some potential negative effects on the environment, including eutrophication (because of the N and P leaching), acidifying pollutants (due to the ammonia emission), pesticide and energy use. And from the animal perspective, current feed composition is not optimal: firstly, up to 80% of phosphorus in cereals feed is stored in the form of phytic acid and difficult for monogastric animals, such as pigs, to digest, ending with the high-phosphorus manure; secondly, pigs cannot utilize proteins (essential amino acids) in the cereals feed efficiently, resulting in an excess of nitrogen excretion in the manure (Dourmad and Jondreville, 2007). Phosphorus and nitrogen from pig manure contributes to eutrophication of freshwater or seawater and greenhouse gas emissions (Velthof et al., 2005).

A promising alternative is using the proteinaceous products seperated from grass to substitute cereals and soya in pig feed (i.e. alternative feeding system, Fig. 1). Grass is an important source of protein. However, traditionally it is believed to be only suitable for feeding ruminant (e.g. cattle, sheep). Grass in the natural state cannot be digested well by pigs. However, with a green bio-refinery (GBR) plant the grass can be made into protein-rich press juice (PJ) and fibre-rich press cake (PJ) (e.g. for production of insulation materials). Proteinaceous concentrate made from juice can be comparable in quality to cereals and soya (Kamm et al., 2010), which reduces the domestic cereal production and import dependence of soya. The residues of the GBR can also be used to produce biogas and be fed back to land as fertilizer with reduced environmental effects.

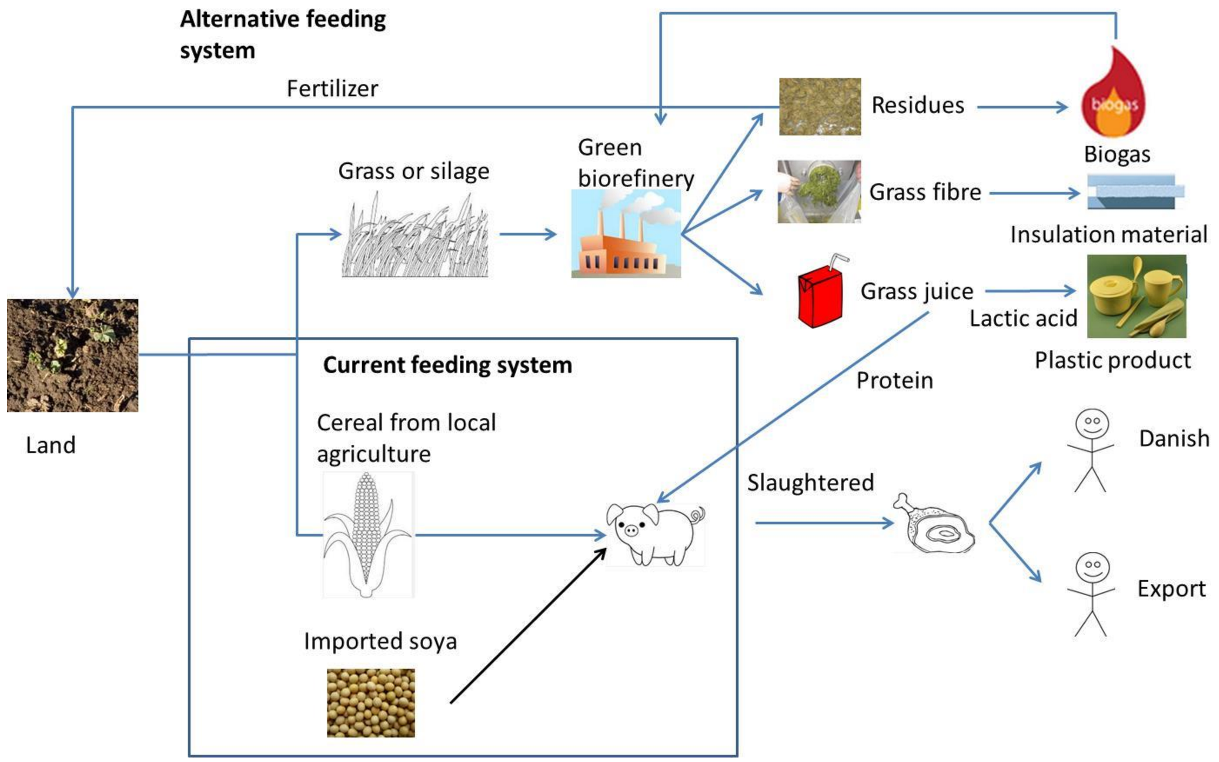

Fig. 1 Current and alternative pig feeding systems

Note: Some pictures are from Sharma et al. (2012)

The idea of adding the ingredient of grass into pig feed is not completely new. Patterson and Walker (1979) examined the use of effluent from grass silage in the pig feed. They found that if silage effluent was included in the pig diet at about 10% of the total dry matter, it could supply almost all the necessary minerals with the possible exception of copper. Numerous studies examined the possibility of adding grass and grass silage as roughage into pig feed (Carlson et al., 1999; Danielsen et al., 2000; Hansen et al., 2006; Lebret, 2008). However, the proportion of grass and silage (in their original state) applied in the pig feed is relatively low due to its low digestibility (e.g. of organic matter and energy (Lindberg and Andersson, 1998)). There are relatively few studies discussing about utilization of proteinaceous concentrates seperated from grass (or silage) in the GBR plants into the pig feed.

The term “green biorefinery, GBR” was defined in the year 1997 as complex systems of sustainable, environment- and resource-friendly technologies for the comprehensive utilization biological raw materials in the form of green and residue biomass (Kamm et al., 1998). The concept, content and goals of green biorefineries are further developed afterwards (Kamm, 2000; Kamm and Kamm, 2004; Narodoslawsky, 1999). Studies about biorefinery mainly focus on investigating the chemical composition of products (Andersen and Kiel, 2000), energy balance (Kamm et al., 2009), processes and operating costs (Kamm et al., 2010; Kamm and Kamm, 2007), etc. O’Keeffe et al. gave a relatively complete assessment for the first generation green biorefinery from the technical (O’Keeffe et al., 2011) and economic (O’Keeffe et al., 2012) perspectives. However, there is still a knowledge gap about linking the GBR with the feeding system to assessment the whole supply chain.

One of the main questions is to evaluate the alternative feeding system (Fig.1) from the economic and environmental perspectives, i.e. if the alternative system can bring economic benefits and (or) reduce adverse environmental effects, compared with the traditional (cereal-based) feeding system. The Danish situation services in this paper as an example. Our research scope therefore includes the two feeding systems and co-products from the GBR (e.g. residues, fibre products). However, we do not investigate the processes with the same cost in these two systems (e.g. slaughter, transportation of pork) or processes outside of Denmark (e.g. the production of soya in South America). The answer for this question could be dependent on market prices, soil condition, animal nutrition and biotechnology, etc., which will be discussed in the uncertainty analysis. The results of this study will pave the way for the large-scale implementation of GBR with pig feed production.

2. Methods and material

For comparison, in the following paragraphs, we investigate both the economic and environmental effects for producing one ton pork within the two feeding systems (cereal-based and alternative) (Fig. 2).

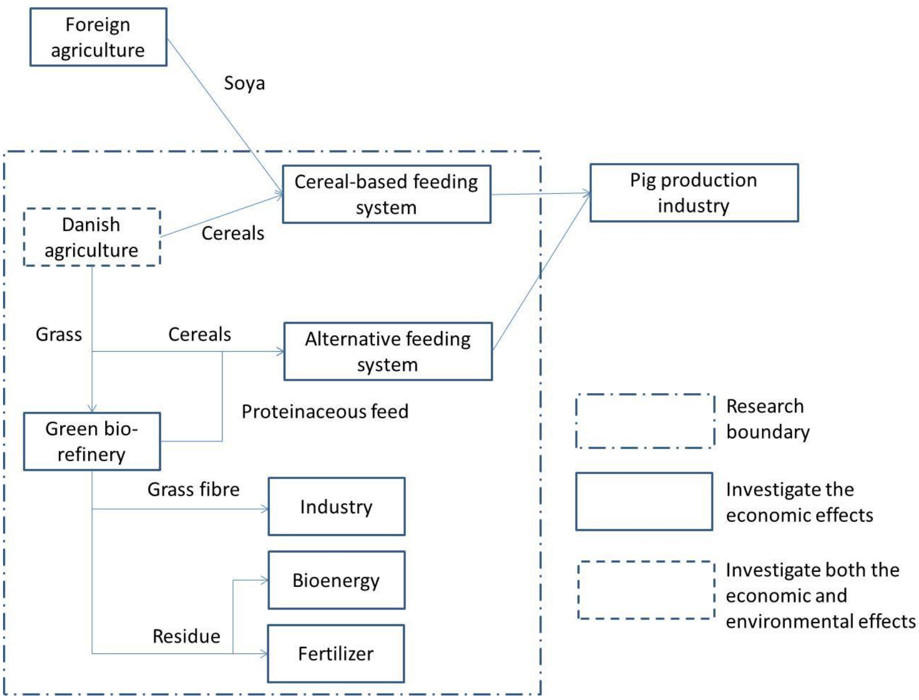

Fig. 2 The research delimitation

2.1 The bio-economic analysis

2.1.1 Pig farmers

Cereal-based feeding system

To produce one ton pork, farmers need to feed both the sow and piglets. To produce one litter of piglets, the sow must go through three stages: gestation, lactation and weaning-to-oestrus interval (WOI). And the piglets also go through three stages: weaner 1 (7-10 kg), weaner 2 (10-30 kg) and finisher (30-105 kg).

We calculate the feed consumption of sow for producing one litter ($C_{c,sow}$) based on the physiological energy value of nutrients and on the standardized digestibility of these nutrients (Tybirk et al., 2013). Specifically, we utilize daily feed consumptions for a sow multiplied by the amount of days in each stage (Hansen, 2012) and then summarize them in three stages. We convert the feed into ingredients according to the typical Danish pig diets for sows in different stages. Therefore, $C_{c,sow}$ can be calculated as follow:

$$C_{c,sow} = T_g \times P \times Fd_g \times F_{c,g} + (T_l \times Fd_l + T_w \times Fd_w) \times P \times F_{c,u} \tag{1}$$

where $T_i,\ i \in \{g, l, w\}$ is the number of days for gestation (g), lactation (l) and the WOI (w) for producing one litter of piglets; $Fd_i\ \ i \in \{g, l, w\}$ is the daily feed required for the sows during the three stages within the traditional feeding system; $P = (p_1, p_2, ..., p_m)$ is the row vector of feed ingredients' prices; $F_{c,i} = (f1_{c,i}, f2_{c,i}, ..., fm_{c,i})',\ i \in \{g, u, w1, w2, f\}$ is the colume vector of feed ingredients required for sows during gestation and other periods (lactation and WOI) and the piglets during the three stages above. Specifically, we use $f1$ to refer to barley. Finally, we divide the cost of sow feeding during three stages ($C_{c,sow}$) by the number of piglets in one litter (n) to get sow feeding cost for producing one piglet, i.e. $C_{c,sow} / n$.

To produce one ton pork, one piglet also needs to go through three stages: weaner 1 (7-10 kg), weaner 2 (10-30 kg) and finisher (30-100kg). The calculation of feed for piglets is mainly based on the feed conversion ratio analysis (FCR) (Agostini et al., 2014; Saintilan et al., 2012). We multiply the gains of one piglet (ΔW) at different stages by corresponding FCRs to get its feed consumptions at different stages and then summarize them. Similarly, we convert the feed consumptions into ingredients. Finally, we divide the sum of feeding cost of sow for producing one piglet ($C_{c,sow} / n$) and feeding cost for one piglet during three stages by the weight of one finisher (W_f) to get the average feeding cost for producing one ton pork (with the cereal-based feeding system), $\overline{C_c}$, as

$$\overline{C_c} = \frac{C_{c,sow} / n + \Delta W_{w1} \times FCR_{w1} \times P \times F_{c,w1} + \Delta W_{w2} \times FCR_{w2} \times P \times F_{c,w2} + \Delta W_f \times FCR_f \times P \times F_{c,f}}{W_f} \quad (2)$$

where $\Delta W_i,\ i \in \{w1, w2, f\}$ are the weight gains for one piglet during the stages of weaner 1, weaner 2 and finisher respectively; $FCR_i,\ i \in \{w1, w2, f\}$ are the feed conversion ratios for the piglets during the three stages, which are defined as the feed consumed divided by the weight gain (Agostini et al., 2014; Saintilan et al., 2012); W_f is the weight for the final finishers (105kg).

Alternative feeding system

Feeding pigs with proteinaceous feed from grass will save the cereals input. The average feeding cost for producing one ton pork with the alternative feeding system (cereals plus proteins), $\overline{C_a}$, is

$$\overline{C_a} = \frac{C_{a,sow} / n_p + \Delta W_{w1} \times FCR_{w1} \times P \times F_{a,w1} + \Delta W_{w2} \times FCR_{w2} \times P \times F_{a,w2} + \Delta W_f \times FCR_f \times P \times F_{a,f}}{W_f} \quad (3)$$

where $C_{a,sow}$ is the feeding cost for sow with alternative feeding system;

$F_{a,i} = (f1_{a,i}, f2_{a,i}, ..., fm_{a,i}, fm+1_{a,i})',\ i \in \{w1, w2, f, g, u\}$ is the colume vector of feed ingredients required for the piglets and sow with the alternative feeding system (refer to "Substituting cereals with proteinaceous concentrate in pig feed" in Section 2.1.2). $fm+1_{a,i}$ is the proteinaceous concentrate input in pig *i*'s feed. And $C_{a,sow}$ is defined as:

$$C_{a,sow} = T_g \times P \times Fd_g \times F_{a,g} + (T_l \times Fd_l + T_w \times Fd_w) \times P \times F_{a,u} \tag{4}$$

2.1.2 GBR plants

We mainly refer to the Danish GBR system (Ambye-Jensen and Adamsen, 2015) combined with the Irish GBR system (O'Keeffe et al., 2011). This section includes two parts: 1) Input-output (IO) analysis of GBR; 2) Substituting cereals with proteinaceous concentrate in pig feed.

IO analysis of GBR

The alternative feed system needs proteinaceous products produced by a GBR plant as an input. A GBR is an integrated system to utilize green biomass (e.g. grass/silage (GS), silage only (S)) as raw materials for the production of industrial products. The GS type GBR uses grass during the summer (about 4 months) and silage for the remainder of the year. The S type GBR uses silage only as the feedstock for the whole year (O'Keeffe et al., 2012).

The GBR system can also be defined according to the input volume. There are three representative input volumes: high volume (HV, 5 t DM (Dry Matter)/h), medium volume (MV, 0.8 t DM/h), and low volume (LV, 0.2 t DM/h).

The technology also affects the GBR's outputs. The basic GBR system (Basic Technology, BT) produces products (e.g. fibre for insulation material, proteinaceous concentrates for pig feed). The advanced GBR system (Advanced Technology, AT) produces fibre and proteinaceous products as well as high-value products (e.g. lactic acid), with technologies of ultra filtration and bipolar electrodialysis. We show the IO flows of GBR in Fig. 3.

Combining the three factors above (feedstock types, input volumes and technologies), we can get nine compound types of GBRs as shown in Table A1. The AT only applies to GBR with silage as feedstock (O'Keeffe et al., 2011).

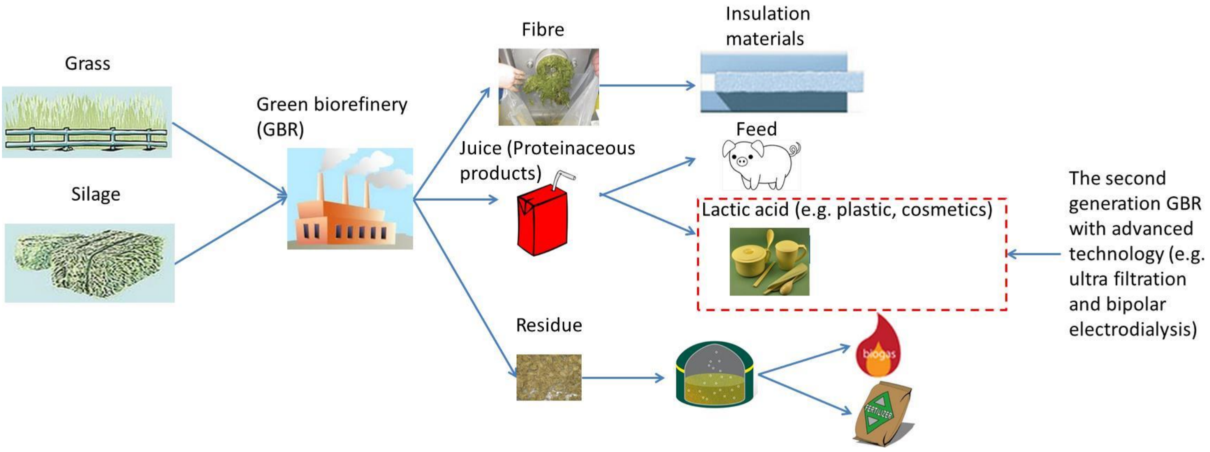

Fig. 3 Input and output of green bio-refinery

Only six GBR types were identified as technically feasible: GSLV, SLV, ATLV, GSMV, SMV, ATMV (O'Keeffe et al., 2011). We mainly refer to the scenario "GSMV" in the economic analysis of O'Keeffe, Schulte et al. (2012). The revenue of a GBR plant, π, for providing proteinaceous concentrate required for one ton pork production is calculate as follows:

$$\pi = (\sum_{i=1}^{3} S_i - C_{fe} - C_{tr} - C_{op} - C_{en} - C_{ot} - C_{ca}) \times \frac{TI_p}{Ou_2} \qquad (5)$$

where S_1 is the sales from fibre products; S_2 is the sales from proteinaceous feed; S_3 is the sales from residues sold to biogas facility; C_{fe} is the cost of feedstock; C_{tr} is the transportation cost; C_{op} is the operational cost; C_{en} is the energy cost; C_{ot} is other cost including overheads and storage; C_{ca} is the capital cost; Ou_2 is the yearly output of proteinaceous feed from a GBR plant; TI_2 is the total input of proteinaceous feed for producing one ton pork and calculated as follows:

$$TI_2 = \frac{\begin{array}{c}(T_g \times Fd_g \times fm + 1_{a,g} + (T_l \times Fd_l + T_w \times Fd_w) \times fm + 1_{a,u}) / n_p \\ + \Delta W_{w1} \times FCR_{w1} \times fm + 1_{a,w1} + \Delta W_{w2} \times FCR_{w2} \times fm + 1_{a,w2} + \Delta W_f \times FCR_f \times fm + 1_{a,f}\end{array}}{W_f} \quad (6)$$

A demonstrating economic analysis of GSMV-type GBR can be found in Table A2.

Substituting cereals with proteinaceous concentrate in pig feed

We mainly use the results of Seppälä et al. (2014). The basic idea is that it is possible to substitute 10% of traditional pig feed with protein concentrate to provide the same energy. The nutritional composition of the protein concentrate from grass in dry matter (DM) is shown in Fig. 4 (Ambye-Jensen and Adamsen, 2015).

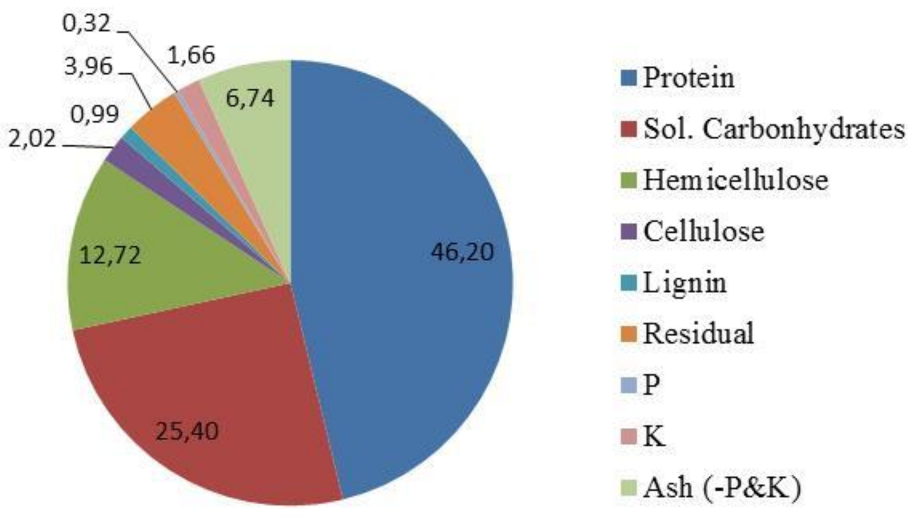

Fig. 4. The nutritional composition (in percentage terms) of the protein concentrate from grass in dry matter (DM)

To obtain the equivalent protein, 3.29 % DM of protein concentrate is equal to 2% soy a plus 8% barley. The alternative feed composition can be found in Table A3.

2.1.3 The environment

We consider the environmental emissions of cultivating grass compared with cereals production and related energy and land use. Due to the data availablity, we do not differentiate the effects between different types of cereals. Instead, we compare the effects of cereals in general and grass. In the analysis of environmental emissions of two feeding systems, we mainly consider two types of effects: nitrogen leaching into the soil and greenhouse gas emissions into the air.

Compared with cereals production, the grass cultivation has longer growing season and permanent root system, which can manage the nutrients more efficiently (Jørgensen et al., 2013). We calculate the nitrogen leaching from cereal and grass production mainly based on Eriksen et al. (2014)'s estimations.

The N-fertilizer application during cereals and grass production also contributes to the greenhouse gas emissions. We calculate the emissions of nitrous oxide nitrogen (N_2O-N, i.e. N that is included in N_2O), e_{N_2O-N}, according to IPCC (2006)'s reseach: the direct emissions from soil was 0.01 kg N_2O-N/kg N fertilizer input, *Ni*. The indirect emissions of N_2O-N are mainly from nitrogen leaching (NO_3-N), *Nl*: 0.0075 kg N_2O-N/kg NO_3-N (IPCC, 2006). Therefore, the emissions of N_2O-N from barley production for producing one ton of pork with the cereal feeding system, Ue_{c,N_2O-N}, can be calculated as follows:

$$Ue_{c,N_2O-N} = 0.01 \times Ni_{barley} \times \frac{Ti_{c,barley}}{Y_{barley}} + 0.0075 \times Nl_{barley} \times \frac{Ti_{c,barley}}{Y_{barley}} \quad (7)$$

where Ni_{barley} is the N fertilizer input for barley production per ha; Nl_{barley} is the nitrogen leaching (NO_3-N) for barley production per ha; Y_{barley} is the barley production per ha; $Ti_{c,barley}$

is the total input of barley for producing one ton pork with cereal feeding system and can be calculated as follows:

$$TI_{c,barley} = \frac{\begin{array}{l}(T_g \times Fd_g \times f1_{c,g} + (T_l \times Fd_l + T_w \times Fd_w) \times f1_{c,u}) / n_p \\ + \Delta W_{w1} \times FCR_{w1} \times f1_{c,w1} + \Delta W_{w2} \times FCR_{w2} \times f1_{c,w2} + \Delta W_f \times FCR_f \times f1_{c,f}\end{array}}{W_f} \quad (8)$$

The emissions of N_2O-N from barley and grass production for producing one ton of pork with the alternative feeding system, Ue_{a,N_2O-N}, can be calculated as follows:

$$\begin{array}{l} Ue_{a,N_2O-N} = 0.01 \times Ni_{barley} \times \frac{Ti_{a,barley}}{Y_{barley}} + 0.0075 \times Nl_{barley} \times \frac{Ti_{a,barley}}{Y_{barley}} \\ +0.01 \times Ni_{grass} \times \frac{Ti_{a,grass}}{Y_{grass}} + 0.0075 \times Nl_{grass} \times \frac{Ti_{a,grass}}{Y_{grass}} \end{array} \quad (9)$$

where $Ti_{a,barley}$ is the total input of barley for producing one ton pork with alternative feeding system and can be calculated as:

$$TI_{a,barley} = \frac{\begin{array}{l}(T_g \times Fd_g \times f1_{a,g} + (T_l \times Fd_l + T_w \times Fd_w) \times f1_{a,u}) / n_p \\ + \Delta W_{w1} \times FCR_{w1} \times f1_{a,w1} + \Delta W_{w2} \times FCR_{w2} \times f1_{a,w2} + \Delta W_f \times FCR_f \times f1_{a,f}\end{array}}{W_f} \quad (10)$$

$Ti_{a,grass}$ is the the total input of grass for producing one ton pork with alternative feeding system and can be calculated as:

$$Ti_{a,grass} = TI_2 \times \frac{FI}{Ou_2} \quad (11)$$

where *FI* is the yearly feedstock input of a GBR plant.

According to Rossier et al. (1998)'s research, the emissions of the mono-nitrogen oxides nitrogen (NO_x-N), Ue_{NO_x-N}, are estimated to be 10% of emissions of N_2O-N. The energy use with the cereal-based feeding system, Eu_c, can be calculated as:

$$Eu_c = UEu_{barley} \times \frac{Ti_{c,barley}}{Y_{barley}} \tag{12}$$

where UEu_{barley} is the energy input per ha of barley production. The energy use with the alternative feeding system, Eu_a, can be calculated as:

$$Eu_a = UEu_{barley} \times \frac{Ti_{a,barley}}{Y_{barley}} + UEu_{grass} \times \frac{Ti_{a,grass}}{Y_{grass}} + UEu_{GBR} \times \frac{Ti_{a,grass}}{fe} \tag{13}$$

where UEu_{grass} is the energy input per ha of grass production; UEu_{GBR} is the yearly net energy input for a GBR plant. The land use with the cereal-based feeding system, Lu_c, can be calculated as:

$$Lu_c = \frac{Ti_{c,barley}}{Y_{barley}} \tag{14}$$

The land use with the cereal-based feeding system, Lu_a, can be calculated as:

$$Lu_a = \frac{Ti_{a,barley}}{Y_{barley}} + \frac{Ti_{a,grass}}{Y_{grass}} \tag{15}$$

All the variables/parameters and their definitions can be found in Table A8.

2.2 Data sources

The basic information of Danish sow productivity, the typical Danish diets for pigs at different stages, and FCRs of weaners and finishers are from the e-book "Nutritional physiology of pigs" of the Danish pig research center (Kjeldsen, 2012) and can be found in

Tables A4, A5 and A6. The crop production data including crop yield, N input and environmental emission data is from Danish agriculture database " landbrugsinfo" while the energy use information is mainly from Dalgaard et al. (2001) and Frame (2005)'s studies (see Table A7).

2.3 Scenarios of uncertainty analysis

In order to explore the robustness of results, we mainly explore the effects of the following uncertainties: (1) variation in sow productivity; (2) price shocks of GBR outputs; (3) variances in soil condition; (4) GBR feedstock composition. For comparision, the parameter setting in the reference scenario can be found in Table A9.

2.3.1 Variation in herd productivity

For the herd productivity, we mainly consider the two variables: (1) sow productivity; (2) productivity of weaners and finishers. We use the variable of weaned pigs/sow/year as an indicator of sow productivity. For the weaners and finishers, we use the feed conversion ratio (FCR) as an indicator of their productivity. As a rule of thumb, the daily FCR is low for young pigs (when relative growth is large) and increases for older pigs (when relative growth tends to level out). Furthermore, when communicating FCR data, it can be desirable to specify feed moisture content and provide information regarding breed, age, feed composition, and environmental conditions under which the ratio applies, to facilitate data interpretation. The variations of these two variables can be seen in Table 1.

2.3.2 Price shocks of GBR outputs

For the price uncertainty, we mainly consider the prices for three outputs (fibre, juice, residue) from GBR which determine its overall profitability. For fibre, it can be made for insulation material whose price is dependent on the technical specification, e.g. the density and heat conductivity (Grass, 2004). According to the related literature and average price of mineral wool insulation with similar technical specifications, the price of fibre is estimated between 0.8 - 1.2 €/kg (O'Keeffe et al., 2012). For the proteinaceous concentrates, it can be used for pig feeding additive whose price is comparable to the price of feeding additive with the same nurient value (amino acids, carotene, fat, etc.) (Sanders, 2012). The range of its price is between 0.15 – 0.39 €/kg (Kamm et al., 2010). For the GBR residues, the reference value is 0.37 €/kg which is dependent on the prices of biogas plant output (e.g. heat, electricity, fertilizer). We simply give a 25% deviation from the reference value (i.e. [0.28, 0.46]) to represent the possible change in its market price (Table 1).

2.3.3 Variances in soil conditions

In 1974, the Danish Ministry of Agriculture established a soil classification which reflects the important soil factors such as topsoil texture, slope and overall drainage conditions. The classification includes 12 soil classes (JB 1-12) (Greve and Breuning-Madsen, 1999). In the agricultural accounting, there are mainly two types of soil condition: (1) JB 1&3, i.e. the sandy soil which is used as the reference scenario; (2) JB 5-6, i.e. the clay soil which will be used in the following uncertainty analysis. The yields and inputs of cereals and grass with the soil type of JB 5-6 can be found in Table 1.

2.3.4 Uncertainties in GBR feedstock composition

Regarding to the feedstock composition, we mainly wonder to investigate the different ratios of press juice (PJ) (or press cake, PC) fraction of fresh matter (FM). In the reference scenario, the ratio of PJ (PC) fraction of FM is set to be 0.6 (0.4). However, the ratio could vary due to different havesting systems and qualities of feedstock. For comparision, we set the ratio of PJ (PC) fraction of FM to be 0.5 (0.5) or 0.7 (0.3). And the proportions of protein contents in PJ and PC (FM) are set to be 0.2 and 0.23 in the reference scenario (Table 1).

Table 1. Parameters setting in the uncertainty analysis

Uncertainties	Scenarios	Parameters setting
Variation in herd productivity	H1 (High sow productivity)	Sow productivity = 29.9 (weaned pigs/sow/year)
	H2 (Low sow productivity)	Sow productivity = 24.8 (weaned pigs/sow/year)
	H3 (Low feed conversion ratio)	FCR (weaner, 7-30kg)=1.77; FCR (finisher, 30-105kg)=2.6
	H4 (High feed conversion ratio)	FCR (weaner, 7-30kg)=2.09; FCR (finisher, 30-105kg)=2.98
Price shocks of GBR outputs	P1 (High output prices)	Price of fibre = 1.2 €/kg Price of proteinaceous feed = 0.39 €/kg Price of residues = 0.46 €/kg
	P2 (Low output prices)	Price of fibre = 0.8 €/kg Price of proteinaceous product = 0.15 €/kg Price of residues = 0.28 €/kg
Variances in soil condition	S1 (clay soil)	Yield of barley: 5500 kg/ha N input of barley: 114 kg/ha Yield of grass: 8360 kg/ha N input of grass: 235 kg/ha
Uncertainties of input-output of GBR	G1 (Low PJ fraction)	The ratio of PJ fraction of FM: 0.5 The ratio of PC fraction of FM: 0.5

	G2 (High PJ fraction)	The ratio of PJ fraction of FM: 0.7 The ratio of PC fraction of FM: 0.3

3. Results

3.1 Comparison of two feeding systems (Reference scenario)

3.1.1 The economic effects

In general, substituting the cereal-based feed with proteinaceous produces is cost-saving for the pig industry. The average decrease in feeding cost is 28.05 €/ton pork (5.01% decrease in the relative term). The gaps between costs of two feeding systems differ in different stages of pork production (Fig. 5). The differences are the largest for raising the finishers (32 €/ton pork, 5.42% decrease in the relative term) and smallest for raising the sows (12.12 €/ton pork, 1.81% decrease in the relative term). The sows' feed includes very little soya, especially for the gestation. Therefore, for the sow feeding the grass juice mainly substitutes the barley which is relatively cheap in the Danish context (167.56€/ton) compared with soya (360.62€/ton), which makes the substitution less cost-efficient. The price of proteinaceous products is 270.78€/ton, which is in between with barley and soya. It is economic to use proteinaceous products to substitute soya but not barley. According to the average substitution ratio (3.29% protein concentrate=8% barley+2% soya), the indifferent substitution price of proteinaceous products should be 626.66 €/ton, with a gap of 355.88 €/ton with its current price level.

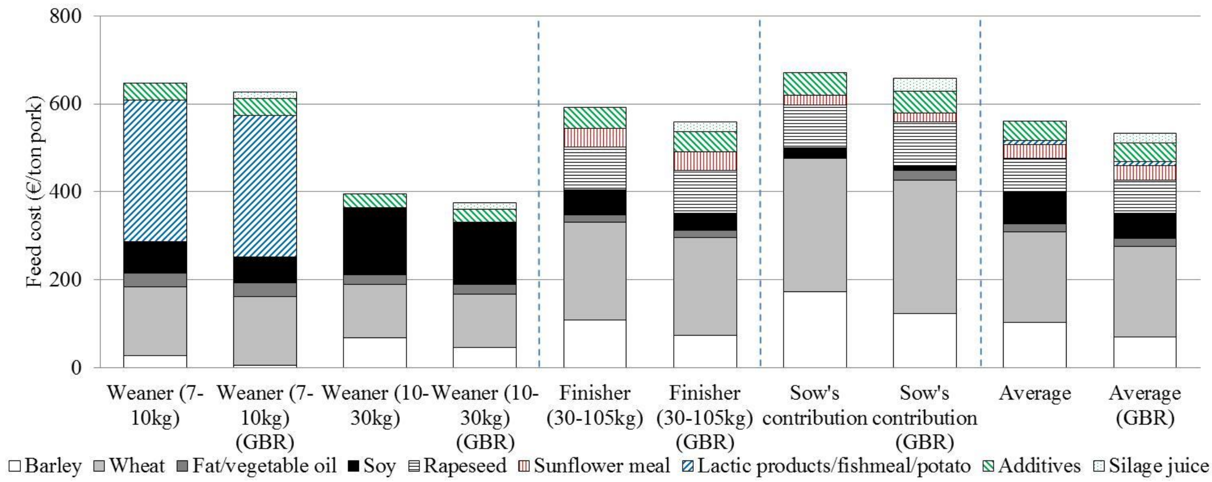

Fig. 5. Comparasion of feeding costs with two systems

The GBR industry is profitable given the technical and market conditions in the reference scenario. For producing one ton pork, the GBR plant needs to produce 0.08 ton protein concentrate with the byproducts of 0.21 ton fibre and 0.03 ton residuces (Fig. 6), which will bring a total revenue of 195.83 € and a profit (before tax) of 96 € . In the sale revenues, the fibre contributes 84.48% followed by protein concentrate (11.05%) and residues (4.47%).

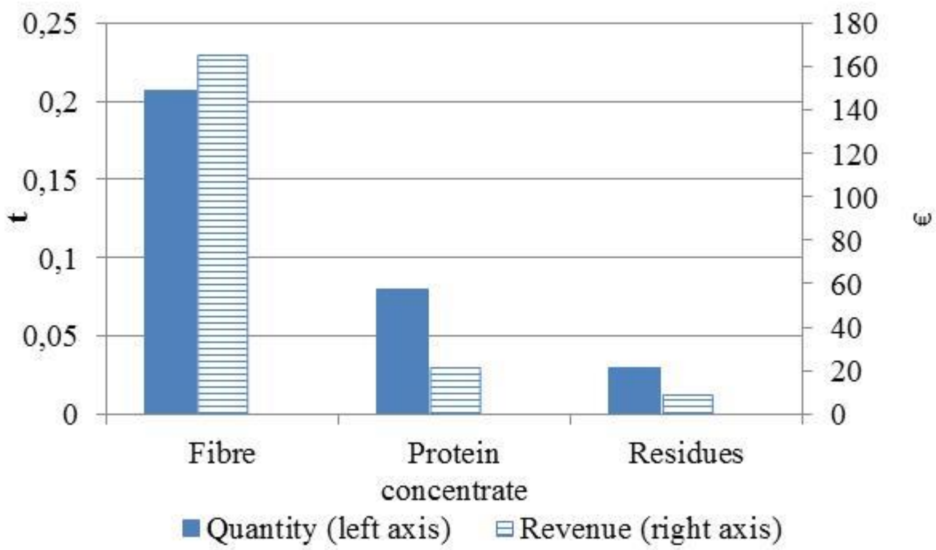

Fig. 6. Physical output and revenue of GBR for producing one ton pork

3.1.2 The environmental effects

To produce one ton pork, with the cereal-based feeding system roughly 0.61 ton barley and 0.2 ton soya are needed. Within the alternative system, less barley (0.42 ton) and soya (0.16 ton) are needed while more grass production (0.32 ton) is necessary. In the following analysis, we will investigate the environmental effects of alternative feeding system from three categories: (1) nitrogen leaching into the soil; (2) nitrogen emission into the air; (3) energy and land use.

Nitrogen leaching (NO_3-N)

To produce one ton pork, the cereal-based feeding needs a nitrogen leaching of 10.01 kg from barley production. In contrast, to produce the same amount of pork the alternative feeding can reduce nitrogen leaching from production of barley and grass by 2.68 kg (26.8% in the relative term), only 7.14% of which is from grass production (Fig. 7). The reasons are: 1) the substition ratio of protein concentrate for cereals is fine; 2) the ratio of protein centrate from grass is high (around 25%).

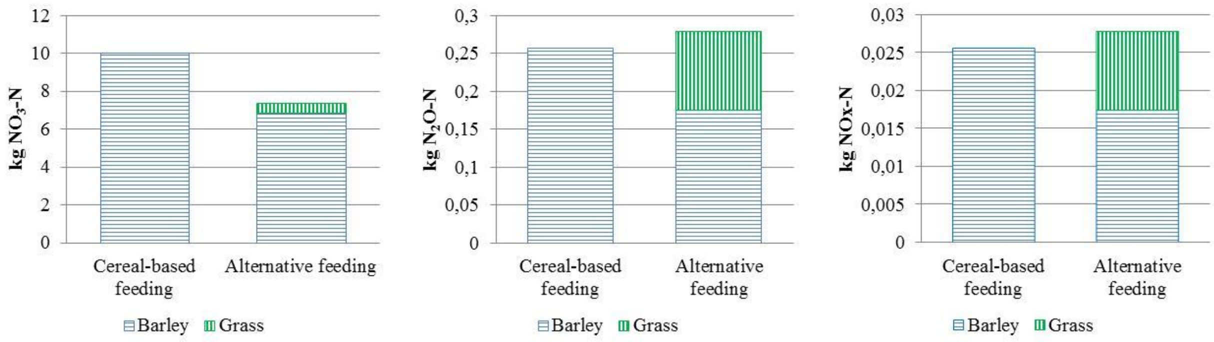

Fig. 7. Nitrogen emissions and their composition from production of barley and grass with two feeding system

Nitrogen emission into the air

To produce one ton pork, the cereal-based feeding system causes emissions of 0.26 kg N_2O-N and 0.0257 kg NO_x–N (Fig. 7) from barley production. In contrast, the alternative feeding needs more N_2O-N emissions (0.279 kg) from barley and grass productions, 37.54% of which are from grass production. The alternative feeding also brings about emissions of 0.028 kg NOx-N, 37.47% of which are from grass production. In sum, substituting cereals-based feeding with proteinaceous products has net increases of 0.023 kg N_2O-N and 0.0022 kg NOx-N for producing one ton pork due to more N inputs needed for grass production.

Energy use and land use

To produce one ton pork, the cereal-based feeding system requires using 2954.94 MJ (megajoules) energy and 0.16 ha land for barley production. In contrast, the energy needed for the feeding with GBR is only 2787.83 MJ, 6.58 % (21.36%) of which is for the operation of GBR plant (production of grass). The feeding with GBR needs less land (i.e. 0.153 ha) for barley and grass production, 28.42 % of which is for grass. In sum, substituting cereals-based feeding with grass has net decreases of 167.12 MJ energy use and 0.008 ha land use for producing one ton pork (Fig. 8).

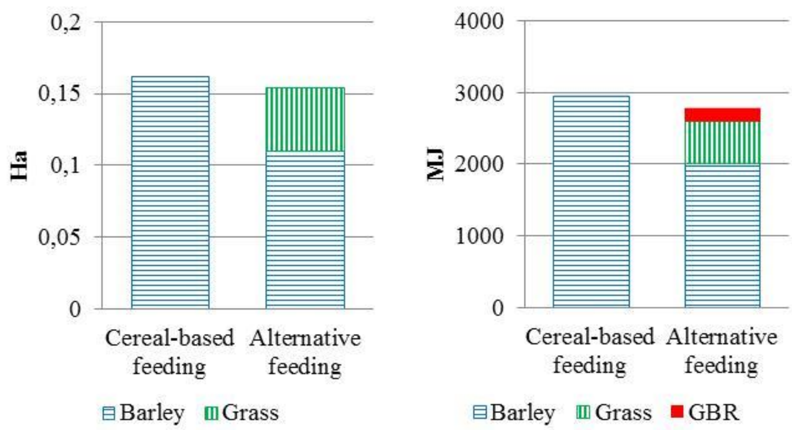

Fig. 8. Energy/land use and their compositions from production of barley and grass and operating GBR within two feeding system

3.2 Uncertainty analysis

3.2.1 Variation in herd productivity

The variations of herd productivity do not affect the conclusion in general, i.e. they do not change the changing trends of impacts of feeding with GBR. Instead they only affect the magnitudes of impact changes. When sows have the high productivity (H1), the cost-saving effect due to substituting with protein feed from GBR becomes weaker because the feed for sow to produce 1 ton pork is reduced. Similarly, the total feed needed for producing one ton pork is also reduced, which therefore reduceds GBR profits. Due to the same reason, in the scenario H1, the environmental effects (NO_3-N, N_2O-N and NO_x-N) and energy and land use are less than the reference scenario (Fig. 9 and Table A10). It is appropriate that H2 has the opposite effects to H1.

The variances of feed conversion ratio have larger effects on the economic and environmental performances than herd productivity. Low FCR (H3) means high pig feeding efficiency, i.e. less feed is needed in producing the same amount of pork. For example, in the scenario H3, the average feeding cost with GBR and GBR profit are reduced by 1.3% and 1.16% respectively for producing one ton pork compared with the reference scenario. The NO_3-N, N_2O-N and NO_x-N with GBR feeding system are also reduced by 1.09%, 1.08% and 1.08% respectively. The energy use and land use with GBR feeding will decrease by 1.05% and 0.85%.

In the scenario H4 with high FCR (low pig feeding efficiency), the opposite effects can be observed. The average feeding cost with GBR and GBR profit are increased by 0.92% and 1.31% respectively for producing one ton pork compared with the reference scenario. The NO_3-N, N_2O-N and NO_x-N with GBR feeding system increase by 1.09%, 1.04% and 1.25%

respectively. The energy use and land use with GBR feeding system increase by 1.19% and 1.44% (Fig. 9 and Table A10).

3.2.2 Price shocks of GBR outputs

The price shocks of GBR outputs mainly affect GBR's profitability and feeding cost. They do not affect the environmental outputs, energy and land use with two feeding systems. In the high price scenario (P1), the average feeding cost increases by 1.77% while GBR profit increase 49.57%. 94.09% of GBR profit is from fibre production. In the low price scenario (P2), the average feeding cost decreases by 1.82% while GBR profit decreases by 5.18% (Fig. 9). Similar as herd productivity, the prices shocks of GBR outputs do only affect magnitudes of impacts but not change the conclusion in general.

3.2.3 Variances in soil conditions

In contrast to price shocks, the variances in soil conditions do not affect GBR profits or feeding costs. Instead, they mainly affects the environmental outputs, energy and land use with two feeding systems. In the scenario of clay soil (S1), the NO_3-N, N_2O-N, NO_x-N, energy and land use decrease by 30.87%, 30.86%, 31.13%, 30.91% and 30.43% respectively with cereals-based feeding. With the alternative feeding, the NO_3-N, N_2O-N, NO_x-N, energy and land use decrease by 29.6%, 24.37%, 24.37%, 25.08% and 25.49% respectively (Fig. 9). However, we can also summarize that the improved soil condition does not change the conclusion in general but widens the gap of environmental outputs, energy and land use between two feeding systems compared with the reference scenario.

3.2.4 Variations in GBR feedstock compositions

GBR feedstock compositions mainly affect GBR profit, environmental outputs, energy and land use instead of feeding cost. Compared with the three uncertainties above, the GBR feedstock compositions have larger effects on GBR profit, environmental outputs, energy and land use. In the scenario of low press juice (PJ) fraction (G1), more grass production is expected for producing the same amount of pork. The GBR profit, NO_3-N, N_2O-N, NO_x-N, Energy and land use increase by 32.38%, 1.64%, 9.32%, 11.1%, 6.99% and 7.19% respectively with the alternative feeding.

In contrast, in the scenario of high PJ (G2), less grass production is needed. The GBR profit, NO_3-N, N_2O-N, NO_x-N, Energy and land use decrease by 34.41%, 1.91%, 10.04%, 10.04%, 7.44% and 7.84% respectively with the alternative feeding. It is noteworthy that the uncentainties in GBR feedstock compositions not only affect the magnitudes of impacts but also subvert the conclusion partly. For example, in G1 scenario the alternative feeding needs more energy and land use (instead of resource saving) than cereal-based system, while in G2 scenario the alternative feeding could also reduce greenhouse gas (N_2O-N and NO_x-N) emissions (Fig. 9).

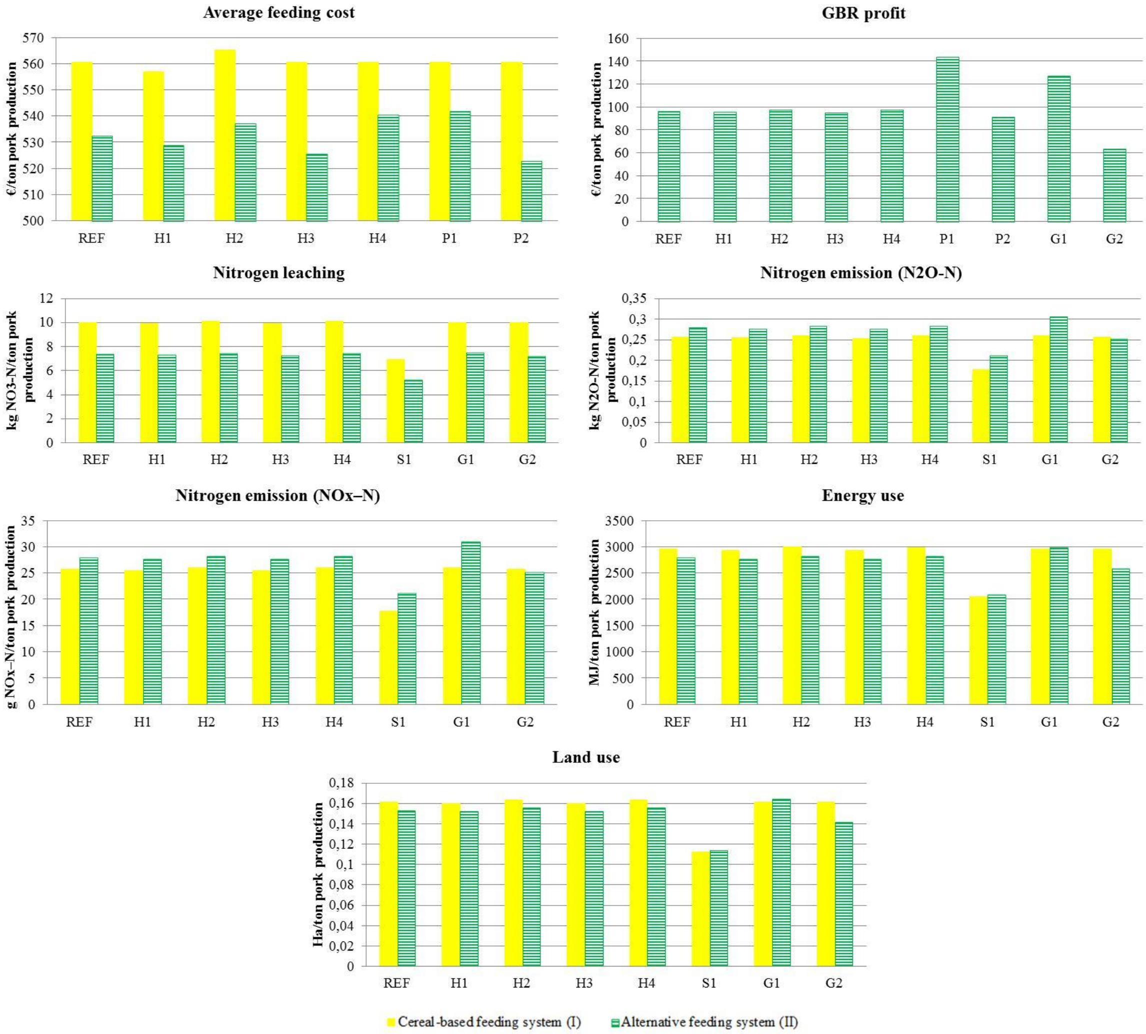

Fig. 9. Results of uncertainty analysis in terms of feeding cost, GBR profit, nitrogen leachning and emissions, energy and land use

4. Discussions

4.1 Economic and environmental peformances of feeding with GBR products

According to our knowledge, there are not any quantative studies about jointly evaluating the effects of substituting cereal-based pig feed with proteinaceous products from GBR plants. The potential barries is that it needs interdisciplinary knowledge ranging from animal nutrition, crop science, economics to biological engineering. This study tries to fill this knowledge gap based on the Danish situation. We use the Danish data of pig feed composition and crop production with input-output analysis of Danish demostrated GBR plant. We find that feeding with proteinaceous products from GBR can save the feeding cost while GBR plants can earn the profits, so called a "win-win" situation exists thanks to the technical progress.

We can also observe a significant reduction (ca 27%) of nitrogen leaching due to feeding with protein products from GBR. However, there are also an minor increase (9%) in the greenhouse gas (N_2O and NO_x) emissions due to increased nitrogen fertilizer applications on the grass production (with a clay soil (S1) the greenhouse gas emissions and resource use are even higher: N_2O and NO_x increase by 19%, energy use increases by 2.3% and land use increases by 1.8%). In this sense, the alternative feeding seems to be a double-edge sword at least regarding to the environmental outputs. A practical way to weigh the benefits of environmental outputs against their costs is to use their shadow prices (in Denmark, the shadow prices of N-leaching, N_2O and NO_x are 40 DKK/kg, 34.52 DKK/kg and 0.055 DKK/kg respectively (Møller and Martinsen, 2013)). To produce one ton pork, the net benefit of environmental outputs is 105.95 DKK (14.24 €). In sum, substituting cereals-based pig feed with protein products from GBR has a double dividend of economic and environmental benefits.

It should be remarkable that the Danish GBR has a relatively high output ratio of protein products (around 25% of the dry weight of feedstock) due to the Danish havesting system and climate condition. And the substitution ratio of protein products to cereals combination is set as 3.29 % DM of protein concentrate is equal to 2% soya plus 8% barley. Both of these two conditions are important for our conclusions in general.

4.2 Uncertainties analysis and its reflections in reality

The analysis of variation in herd productivity extends our knowledge into countries and regions with different levels of animal husbandry. The Danish sow productivity is higher than most of the EU countries[1]. For example, Poland and Hungary have low sow productivity (17.5 and 16.8 pigs/sow/year in 2015, respectively) and are corresponding to the H2 scenario. The sow productivity is determined jointly by the litter size and piglet mortality. The Danish sows have a higher litter size than other pig producing countries but also a high mortality (Kjeldsen, 2012). However, the mortality could be reduced due to improved management, e.g. genetic modification, optimized nutrition and temperature control in the pigsty, which could increase the sow productivity and be corresponding to the H1 scenario.

Feed conversion ratio (FCR) is an important factor for the economy of pig production because feed cost constitutes around 60% of all variable costs. Denmark is one of the leading countries in term of feed conversion efficiency. Some European countries, e.g. Italy and Spain, have higher FCR (because the slaughtering weight is higher, e.g. in Italy it is 160 kg) and could be corresponding to the H4 scenario. Although there is only one breeding system in Denmark, there are large variations between farms in feed conversion efficiency due to on-farm conditions, e.g. feed composition, climate, housing conditions and health. Farms with better on-farm conditions are expected to have lower FCR and corresponding to H3.

The market conditions are also important factors affecting the economics of GBR plants and pig farms. The price of protein products is affected by the cost of a comparable amount of cereals-based pig feed. The price of fibre products as, e.g. insulation materials, is driven by the growth of construction industry in emerging economies and re-insulation market in the developed economy. The price of residues is determined by the demand of bioenergy and agricultural fertilizers. All of these three prices could rise or fall due to the uncertainties in economic development. The construction industry is expected to grow over the next decade, especially in the rapidly emerging economies of Asia, e.g. China and India. And in western Europe, insulation materials are used increasingly to reduce energy consumption. The feed

[1] http://pork.ahdb.org.uk/prices-stats/costings-herd-performance/eu-sow-productivity/

market is more uncertain due to the decline in demand from the EU pig sector. The supply of fertilizer increases quicker than its demand (NATIONS, 2015), implying the value of residues could have a downward trend.

The economic and environmental performances of feeding with GBR protein products are also highly dependent on the soil condition. Overall the soils of western Denmark contain a high sand percentage (the reference scenario), whereas the eastern parts are dominated by the clay soils (the scenario S1)[2]. According to the results, the nitrogen reduction effect is weaker in the clay soils, e.g. the eastern part. Therefore, it is better to firstly introduce the GRB industry chain in western Denmark, e.g. Jutland.

Among the four uncertainties, the GBR feedstock composition is the most important one, which could even subvert the conclusion partly. Thanks to the climate condition and Danish havesting system, the grass has a relatively high fraction of pressed juice and also the protein. However, in some countries or regions, e.g. Ireland, the output of protein products is only equal to 7% of feedstock in dry weight. In such cases (scenario G1), the requirement of grass production is highly increased which could deteriorate the environmental benefits of feeding with GBR protein products and even subvert the conclusion in general.

4.3 Future directions

Currently there is a lack of laboratory results about the digestability of protein products compared with cereal-based feed in Danish feeding system. The real substitution ratio of protein products with cereals can be used when the further results are available. There are still not large-scale implementation of GBR plants in Denmark. And the real business operation data is still lacking. The incentives for farmers to switch to grass productions need to be analyzed further because currently profits of grass production are less than cereal production.

[2] http://dnmark.org/?page_id=1314&lang=en

Regarding the GBR feedstock composition, we only study the effects of pressed juice (cake) fraction in fresh biomass. However, the fraction constituents (e.g. fibre, protein content in pressed juice) may also vary dependent on different growing conditions.

Finally, we do not explicitly study the environmental benefits of reduced soya production in South America, which could also be very significant from the global perspective.

5. Conclusions

The increasing world population needs more and more high-quality proteins and nutrients from livestock production. However, there is a large challenge about how to promote the livestock production in a sustainable way. It is undoubted that all feed production has environmental impacts. One important impact is nitrogen leaching and resulting eutrophication (Nørring and Jørgensen, 2009). One way to relieve the nitrogen leaching is to use grass proteins to substitute part of cereals-based pig feed.

Actually the idea of extraction of leaf protein is not new. However, there is no significant industrial implementation, at least in Denmark, due to the competitive price and convenience of cereals feed. Recently, the Denmark has an ambitious plan to increase the production of biomass from agriculture and forestry by 10 million tons (Gylling et al., 2013). With this background, it is interesting to investigate if the green biorefinery (GBR) can provides a possibility of both the economic and environmental benefits for pig feeding system.

In this paper, we find that substituting cereals-based pig feed with protein products from GBR has the economic benefits for both pig production industry and GBR plants. The average feeding cost can reduce by 5%. The cost saving is the largest for the finisher feed and smallest for the sow feed. At the same time, the GBR plant can make a profit of 96€ for providing protein products to produce one ton pork, 84.48% of which is from the revenue of fibre products.

Substituting cereals-based feed with protein products also has the (net) environmental benefits. Feeding with protein products from GBR can reduce the nitrogen leaching (NO_3-N) by 26.8% while increasing the greenhouse gas emissions moderately (N_2O-N by 8.98%, NO_x-N by 8.56%). It can also save energy and land use by 5.66% and 4.97% respectively.

The uncertainty analysis shows: (1) when sows have the high (low) productivity, the cost-saving effect and (net) environmental benefits become weaker (stronger); with the low (high) feed conversion ratio, the cost-saving effect becomes stronger (weaker) while the environmental benefits change slightly; (2) when GBR output prices are high (low), the cost-saving effect for feeding is reduced (increased) while the GBR plants' profits become larger (smaller); (3) with improved soil conditions the (net) environmental benefits become smaller while more energy and soil resource are needed; (4) with high (low) pressed juice in fresh grass more (less) environmental benefits and less (more) resource use are expected although the GBR plants' profits become less (more).

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