Future Atmospheric CO_2 Concentration and Environmental Consequences for the Feed Market: a Consequential LCA

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ABSTRACT

With the rising atmospheric carbon dioxide concentration [CO_2], crops will assimilate more carbon. This will increase yields in terms of carbohydrates but dilute the content of protein and minerals in crops. This consequential life cycle assessment study modelled the environmental consequences that such altered chemical composition and crop yields would have for the production of pig feed. Results revealed, among others, that an extra European demand of pig feed under an atmospheric [CO_2] of 550 µmole mole^{-1} would lead to ca. 6% less expansion of additional arable land worldwide, in comparison to feed produced under today's conditions. However, this did not translate into lower greenhouse gas emissions, because the benefit of increased crop yield was counteracted by changes in the composition of the feed formulation. Among the important changes, feed produced under high [CO_2] was shown to integrate 23% more soymeal and 5% less wheat than at present.

Keywords: Compound pig feed formulation, consequential life cycle assessment, land use changes, amino acids.

1. Introduction

During this century, the rising atmospheric carbon dioxide concentration ([CO_2]) is expected to increase crop yield due to increased carbon assimilation, for example in wheat grains by 10% (Högy et al. 2009). On the other hand, the higher carbon uptake causes increased starch content and, consequently, also a dilution of the relative protein and mineral content in food and feed crops.

The animal feed market, which currently absorbs approximately 45%, 58%, and 80% of the world cereal, maize and soy, respectively (International Grain Council 2012), is likely to be affected by such changes in crop yield and composition. In fact, as the composition of animal feed for intensive livestock production is carefully optimized in order to meet both the applying legislation and the nutritional requirements in a cost-effective manner, any change in both the chemical composition and the yield of feed crops will affect the future formulation of the feed.

Although the environmental consequences of the forecasted future increases in meat (and thus feed) demand have been overly studied (e.g. Steinfeld et al. 2006; Nellemann et al. 2009; Meul et al. 2012), there are no studies, to the authors' knowledge, that attempted to address the environmental impacts related to the changes that a higher [CO_2] would induce to the feed market. On an environmental perspective, a (CO_2-induced) higher crop yield would contribute to reduce both the land use and the land use changes associated with increased demand for animal feed. On the other hand, lower protein content would trigger an increased need for protein-rich crops like soybeans, which in turns would involve an increased land use change, the environmental impact of which may be considerable (e.g. Searchinger et al. 2008; Gibbs et al. 2008; Hamelin et al. 2014). Yet, it is not clear which effect would dominate over the other. Further, a change in protein content has to be addressed with regards to the specific amino acids affected, as a change in some non-essential amino acids (e.g. proline) is rather meaningless for the overall feed composition.

Focusing on the effects of elevated [CO_2] alone, this study endeavours to assess the environmental consequences of compound pig feed grown at the "present" atmospheric [CO_2] (taken at 380 µmole CO_2 mole^{-1} dry air) and at a "future" [CO_2] (550 µmole mole^{-1} dry air by 2050; IPCC 2007). From this point onwards, the former will be referred to as "present feed", and the latter, as "future feed" with the understanding that these are both compound feeds. Compound (or complete) feed means multi-component feed produced at a competitive price to satisfy all nutritional and technical needs in terms of carbohydrates, protein, oils, fibre, enzymes, vitamins, etc.

2. Methods

2.1. Feed Formulation

For a market-based approach, the feed formulation software Bestmix® (Adifo Software 2014) was used to establish both the present and future feed formulation for piglets, sows and slaughter pigs (a feed mix consisting of 20% piglet feed, 20% sow feed and 60% fattening pig feed was considered). Through optimization algorithms, Bestmix® formulated the best compromise between profitability, nutritional value and animal health, while ensuring that the Danish and European legal requirements of the feed are met. This procedure allowed determining the exact ingredients constituting the present and future pig feed, and in which proportion.

One important input to Bestmix® is the chemical composition of crop ingredients, in terms of starch, protein, amino acids and macro- and micro-nutrients, for both today's and future's conditions (Table 1). Another important input parameter to Bestmix® is the price of feed ingredients. However, as the aim of this study is primarily to investigate the consequences of crops' composition changes, and as no reliable estimate is available on future crop prices, prices of crop ingredients under a high [CO_2] future were taken to be equal to the present prices.

2.2. LCA Model

The functional unit to which all input and output flows were related is "the production of one extra tonne of pig feed". Background LCA data (e.g. fertilizers, electricity, etc.) were taken from the Ecoinvent v.2.2 database (Ecoinvent Centre 2014), while foreground data were essentially related to the cultivation, yield and chemical composition of the crops used in the feed formulation. The geographical scope considered for the foreground system was Denmark, i.e. the pig feed was considered to be manufactured for the Danish market. The Danish example is taken as representative for most industrialized countries in a temperate climate. The chosen method of normalization was to monetize the environmental impacts (expressed in €2003; Stepwise2006 v1.2 impact assessment method, Weidema 2009). Although the results from this step are not presented here, this allowed the selection of the key characterized impact categories for this study; global warming (100y horizon), nature occupation, respiratory inorganics and non-carcinogenic human toxicity.

All processes affected by the production of 1 tonne of pig feed, i.e. from crop cultivation to harvest, and up to the mixing of the feed were included in the LCA system boundary, including, among others, the cascading effects induced by a change in the biochemical composition of the ingredients. This change implies an overall change in the feed formulation, both in terms of the ingredients employed and in their quantities in the feed, which was quantified though Bestmix® (output of Bestmix®; Table 2).

2.3. System Boundary of Crop Ingredient and Life Cycle Inventory (LCI)

This study involves 5 main crop ingredients, and for all these, land use changes were taken into account. The wheat needed for the pig feed considered in this case study is grown in Denmark. In a country like Denmark, where 65% of the total land is already used for cropland and where policies have been adopted in order to double the forested area (nowadays representing ca. 13% of the total land; Nielsen et al. 2011), very limited conversion from forest or alike nature types is occurring. Most likely, the land needed to grow this extra wheat will be taken from actual Danish cropland, involving that one crop cultivated today will be displaced. Such a displaced crop is, in consequential LCA, referred to as the marginal crop. In this study, the marginal crop was assumed to be spring barley (a carbohydrate crop), based on Schmidt (2007) and Dalgaard et al. (2008). The environmental consequences of cultivating wheat instead of the spring barley that was already cultivated represent, in this case, the so-called direct land use changes (dLUC).

Table 1. Chemical composition and yield of the four main crop ingredients, at present (380 μmole mole^{-1}) and future (550 μmole mole^{-1}) atmospheric CO_2-concentration

	Wheat, Denmark			Barley, Denmark			Soy, Argentina/Brazil			Rapeseed, Germany		
Chemical composition	Present[1]	Change[2] (%)	Future	Present[1]	Change[3, 4] (%)	Future	Present[1]	Change[3] (%)	Future	Present[1]	Change[5] (%)	Future
Total Dry Matter, %	85	0	85	85	0	85	88	unknown	unknown	89	unknown	unknown
Starch (g/kg)	670	+7.5	720	630	+4.1[4]	660	27	unknown	unknown	19	unknown	unknown
Raw Protein, %	9.5	-14	8.2	9.7	-15[3]	8.2	47	-1.4	46	35	-4.6	33
Amino Acids (g/kg)												
Lysine	2.3	-10	2.0	2.6	unknown	unknown	26	unknown	unknown	15	-2.5	14
Methionine	1.3	-17	1.1	1.4	unknown	unknown	5.7	unknown	unknown	6.0	-4.3	5.7
Cystine	1.9	-17	1.6	1.8	unknown	unknown	5.8	unknown	unknown	7.0	-5.4	6.6
Threonine	2.2	-21	1.8	2.4	unknown	unknown	16	unknown	unknown	12	-1.8	11
Tryptophan	0.93	-17	0.77	0.93	unknown	unknown	5.7	unknown	unknown	3.3	-3.1	3.2
Isoleucine	2.8	-22	2.2	2.7	unknown	unknown	18	unknown	unknown	11	-3.1	10
Leucine	5.2	-19	4.2	5.1	unknown	unknown	32	unknown	unknown	20	-3.7	19
Histidine	1.9	-16	1.6	1.7	unknown	unknown	11	unknown	unknown	8.1	-3.9	7.7
Phenylalanine	3.6	-14	3.1	3.7	unknown	unknown	21	unknown	unknown	11	-1.9	11
Tyrosine	2.4	-16	2.0	2.3	unknown	unknown	16	unknown	unknown	8.2	-2.6	8.0
Valine	3.5	-8	3.2	3.6	unknown	unknown	20	unknown	unknown	14	-3.4	13
Macro-elements (g/kg)					(4)							
Calcium	0.43	-15	0.36	0.43	4.8	0.45	3.5	unknown	unknown	8.5	-1.5	8.4
Phosphorus	2.6	-4	2.5	3.0	-4.6	2.8	6.8	unknown	unknown	11	1.8	11
Sodium	0.085	-6	0.080	0.17	unknown	unknown	0.18	unknown	unknown	0.36	0.1	0.36
Potassium	5.0	-1	4.9	4.8	0	4.8	22	unknown	unknown	13	0.3	13
Magnesium	1.0	-7	0.95	1.0	-3.3	0.99	3.2	unknown	unknown	4.7	0.8	4.8
Sulphur	1.1	-13	0.96	0.94	-5.0	0.89	3.6	unknown	unknown	6.5	-6.1	6.1
Micro-elements (mg/kg)					(4)							
Iron	27	-18	22	29	-11	26	260	unknown	unknown	230	1.0	230
Manganese	25	-3	24	12	unknown	unknown	47	unknown	unknown	68	-2.6	66
Zink	34	-13	30	24	-13	21	48	unknown	unknown	65	-5.6	61
Yield (t fm ha^{-1})	6.8[6]	+ 11%[5]	7.3	5.0[6]	+20%[8]	6.0	3.4[9]	+15%[10]	3.9	3.8[11]	+ 5.0%[12]	4.0

[1] VSP 2012; [2] Högy and Fangmeier 2008; [3] Taub et al. 2008; [4] Erbs et al. 2010; [5] Högy et al. 2010 (extrapolation assuming linear responses to elevated [CO_2]); [6] Hamelin et al. 2012; [7] Högy et al. 2009 (extrapolation assuming linear responses to elevated [CO_2]); [8] Fangmeier et al. 2000; [9] Dalgaard et al. 2008; [10] Morgan et al. 2005; [11] FAOSTAT 2014 (average 2005-2010); [12] Clausen et al. 2011.

Indirect land use changes (iLUC), on the other hand, represent the environmental consequences related to how this missing supply of Danish spring barley will be supplied on the world market. Such increased crop production may stem from increased yield, also referred to as intensification, or from land conversion to cropland, also referred to as agricultural land expansion. Both were taken into account, as further described in 2.4.

Barley, rapeseed meal and sunflower meal were also considered to be imported from Europe. Similarly to wheat, an increased demand for land in Europe in order to cultivate the barley, rapeseed (rapeseed meal) and sunflower (sunflower meal) resulting from an extra demand of Danish pig feed was considered to take place at the expense of spring barley. In the case of rapeseed and sunflower, the meal needed for the feed is however co-produced with respective rape and sunflower oil, leading to a corresponding decrease production and supply of the marginal oil, here taken as palm oil (Schmidt 2007; Dalgaard et al. 2008). In terms of land use changes, this represents an avoided cultivation from the marginal supplier of palm oil, here considered to be South-East Asia, where the largest increases occurred since the mid-1960s, as highlighted by the production statistics from the Food and Agriculture Organization (FAO) of the United Nations (FAOSTAT 2014). Yet, along with this palm oil, palm meal would have been produced as well (Schmidt 2007). As a result of the no longer produced palm meal (supplying both carbohydrates and protein), the cultivation of the marginal source of carbohydrate and protein is induced, here taken as Canadian barley (Schmidt 2007) and soybean meal (Dalgaard et al. 2008), respectively. Because the production of the marginal protein, soybean meal, interacts with the oil market again, a loop system is thus created, and this loop should be stopped at the point where the consequences are so small (i.e. when the differences between two subsequent iterations approach zero), that any further expansion of the boundaries would yield no significant information for decision support (Ekvall and Weidema 2004). These cascading effects are referred to as the "oil-meal loop". The substitution ratios were quantified on the basis of the carbohydrates and lysine content of the displaced and induced/avoided crops. The content in lysine was used instead of the crop’s content in total protein; it is in fact the composition of the protein in terms of amino acids, or rather in terms of limiting amino acids, which matters for feed, and lysine is the most important limiting amino acid in pig feed.

For soybean meal, based on an analysis of the historical data available in the statistical database of FAO (FAOstat, 2014), soybean meal from Argentina and Brazil was identified as the one most likely to react to an increase in demand for soy. For palm fatty acid distillates (palm fruit), as above-mentioned, the palm meal from South-East Asia was considered. The system expansion considered for these two oil crops is as described above, both involving the oil-meal loop.

For fermentation-based amino acids, which are produced from of a mix of different crops, the same principles as described above were applied to define the system boundary.

The inventory data for barley and wheat cultivation in Denmark were taken from Hamelin et al. (2012; wet climate, sandy soil), while life cycle inventory (LCI) data from the Ecoinvent (v.2.2) database were used to model the cultivation of imported soybean (Brazil), rapeseed (Germany), sunflower (Spain) and palm oil (Malaysia). For fermentation-based amino acids, the generic recipe of (Mosnier et al. 2011) was used, while all enzymes and vitamins were modelled as phytase, this being the best proxy found given the availability of LCI datasets at the time of modelling. For other ingredients (mineral, salts, fish meals), LCI datasets from the Ecoinvent (v.2.2) database were used.

2.4. Land Use Changes

In this study, the iLUC impact was defined as the sum of: 1) net arable land expansion, 2) intensification, and 3) cultivation of the reacting crop on the new agricultural land. To quantify this impact, it is necessary to identify: i) which regions are likely to be affected; ii) in these, which types of biomes are converted; iii) in each affected region, how much land is affected and how (i.e., expected share of intensification and expansion); iv) C losses from the converted land; v) changed use of N-fertilizers associated with intensification; vi) cultivation practices for the crops established on the cleared land.

To this end, the approach described in (Hamelin et al. 2012b) was applied. The reader is referred to this, and to Hamelin (2013) and Tonini et al. 2012, for additional details on the modelling of land use changes.

3. Results

Table 2 presents the optimization output performed in Bestmix®, i.e. the composition of present and future compound pig feed based on the biochemical composition of the main crop ingredients (Table 1) and the current price of these. The results in Table 2 support the hypothesis that pig feed based on wheat, barley and rape grown in Northern Europe under higher [CO_2] will need a higher supplement of protein as well as less carbohydrate ingredients. Table 2 also highlights that both present and future feed consist of at least 46% wheat, 25% barley, 9% soy meal, 7% rape meal and 4% sunflower seeds, these five ingredients making up approximately 93% of the feed.

Characterized LCA results are presented in Table 3, with focus on the four socio-economically most important impact categories identified through normalization in Stepwise 2006, as described in 2.2.

Table 2. Change in ingredients of compound pig feed under a future [CO2] (550 ppm) (output of Bestmix®)[1]

Product	Main function in the feed	Amount in compound pig feed		
		present (kg t^{-1} feed)	future (kg t^{-1} feed)	relative change
Wheat	Energy	479.9	455.2	-5.1%
Barley	Energy	250.0	250.0	0.0%
Soy meal	Protein	92.2	113.7	+23%
Rape meal	Protein	68.0	68.0	0.0%
Sunflower meal	Protein	42.0	42.0	0.0%
Beet molasses	Energy	17.0	20.0	+18%
PFAD[2] oil	Energy and technical aid	13.4	13.0	-2.9%
Chalk (lime) $CaCO_3$	Health	12.0	11.7	-2.1%
Amino acids (fermentation[3])	Health	5.1	4.3	- 16%
Salt, sodium chloride	Health	4.5	4.5	+ 6.3%
Mono calcium phosphate	Health	4.3	4.7	+ 5.5%
Protein (from fish)	Protein	4.0	4.0	0.0%
Vitamins	Health	3.2	3.2	0.0%
Phytase and xylanase	Health, economy, environment	0.8	0.8	0.0%
Dl-methionine (synthetic)	Health	0.2	0.3	+ 14%
Haemoglobin meal	Protein	2.0	3.4	+ 65%
Formic acid, calcium salt	pH-adjustment	1.16	1.16	0.0%

[1] The number of digits does not reflect the precision; these are simply shown in order to facilitate the comparison between the different feed ingredients; [2]Palm fatty acid distillate; [3]Includes lysine, threonine and tryptophan.

Table 3. Characterized LCA results for the most important impact categories, as identified by the monetized normalization in Stepwise, split up per feed ingredient[1]

	Non-carcinogenic human toxicity (kg C_2H_3Cl-eq. per t pig feed)		Respiratory inorganics (kg $PM_{2.5}$-eq. per t pig feed)		Nature occupation (m^2 agricultural land per t pig feed)		Global warming (kg CO_2-eq. per t pig feed)	
	Present	Future	Present	Future	Present	Future	Present	Future
Amino acids (fermentation)	-3.62	-2.44	-0.046	-0.030	-117	-76	-67	-45
Barley	2.74	2.50	0.079	0.072	172	157	162	150
Palm oil	-0.76	-0.64	0.088	0.075	-0	-0	51	43
Rape	30.40	24.17	-0.220	-0.193	140	119	-4	-14
Soy	-6.61	-7.15	0.375	0.418	185	202	409	450
Sunflower	-7.59	-6.09	-0.105	-0.086	478	406	42	44
Wheat	31.12	27.16	0.200	0.182	258	243	-9	13
Others	0.10	0.10	0.018	0.019	1	1	30	30
Net	*45.78*	*37.51*	*0.389*	*0.457*	*1117*	*1051*	*613*	*671*

[1] The number of digits does not reflect the precision; these are simply shown in order to facilitate the comparison between the different feed ingredients.

4. Discussion

The environmental impact of producing one extra tonne of compound pig feed was expected to decrease in the high [CO_2] future due to the higher yields (and thus lower land use) caused by the higher CO_2 uptake from the atmosphere. But even though the yield increases were found to be non-negligible, e.g. 10% for wheat and 28% for rape (Table 1), the net land use did not decrease to the same extent. Still, however, the net fall in land use per tonne of pig feed was found to be around 6% (Table 3). Unexpectedly, this did not lead to a net fall in greenhouse gas emissions per tonne of feed, on the contrary it increased by 9% for crops grown at the future [CO_2]. This is essentially due to the change in feed composition, where considerably more soybean meal is required under a high [CO_2] (23% more; Table 2), which involves the conversion of biomes with relatively high C stocks.

The biggest differences, however, are found for the impact categories respiratory inorganics (fine particles) and non-carcinogenic human toxicity (17% increase and 18% decrease, respectively). Again, these differences between the present and future [CO_2] scenarios can be explained by the change in feed's chemical composition, especially the increased need for soy meal and decreased need for wheat (Table 2).

For all impact categories, nearly all impacts are caused by the crop-based ingredients, i.e. the sum of others (non-crop ingredients) is infinitesimal (Table 3). For non-carcinogenic human toxicity, rape and wheat are the biggest contributors (caused by the agrochemicals used for rape and wheat cultivation, but for wheat much reduced by the displaced barley). For respiratory inorganics, soy and wheat are the major contributors (caused by soy and wheat cultivation, but for wheat much reduced by the displaced barley, and for soy somewhat reduced by soy oil displacing palm oil), while rape contributes negatively (mainly due to displaced palm oil). For nature occupation all the main crop ingredients contribute, and sunflower the most (due to the low yield of sunflower cultivation and the displaced barley). For global warming, soy is the biggest overall contributor (essentially because of iLUC), followed by barley. Amino acids produced by fermentation contribute negatively to each of the main impact categories. This is because sugar production (one of the substrates in the fermentation process producing amino acids) gives rise to by-products (molasses and pulp) which can substitute the use of marginal carbohydrates for animal feed. The saved carbohydrates production (and the land use changes it would have generated) had a greater negative impact than the positive impact from the consumed sugar substrate. Yet, these effects are of course highly dependent upon the data quality used to model them. As three crop ingredients are used to produce these amino acids (sugar beet for the sugar input, corn for the corn starch input and wheat for the wheat starch input), and as each of these crops involve at least three co-products, a considerable degree of uncertainty is introduced in the model, as a result of the numerous assumptions involved regarding the displacement effects (i.e. system expansion).

One limit of this study is that it only focussed on the effect of elevated [CO_2] to represent the future conditions under which pig feed will be produced. In fact, higher atmospheric [CO_2] is not the only global change to determine the yield and the chemical composition of crops in the future. The results of this study are thus not to be seen as representative of the future state of global climate and meteorological conditions (data for this is as yet unavailable), but as an illustration of the cascading consequences a change in crop yield and composition (in this case triggered by an increase in atmospheric [CO_2]) can have for pig feed formulation. As for any LCA, the results of this study are closely linked to the quality of the inventory data and assumptions taken. For example, no changes in amino acid composition were considered for barley and soy as a result of increased [CO_2], because no data or reliable estimation proxy could be found. Nevertheless, the study provides a solid framework for assessing the consequences a changed crop composition due to elevated atmospheric [CO_2] would have on pig feed, which was not, to authors' knowledge, available so far.

Another limit is that the changes in manure composition resulting from a change in feed composition have not been taken into account. In fact, a feed containing less protein from cereals (which are difficult to digest) but more easily digestible protein from e.g. soy or rapeseed meal, involves a better digestion, and thus a reduction in excreted N can be expected. This could have consequences for the subsequent use of the manure as a fertilizer, as it would involve a reduced potential for emission of N flows (e.g. ammonia, nitrous oxide, nitrate losses). Based on Table 2, considering these induced changes in manure composition would likely have induced additional benefits for the future pig feed, which comprises significantly more soymeal and less wheat.

Finally, one of the most important sources of uncertainty probably lies in the estimation of the environmental consequences generated by land use changes, as clearly emphasized in several publications already (e.g. Plevin et al. 2010; Warner et al. 2013). Nevertheless, it should be highlighted that although the actual magnitude of environmental impacts related to land use changes is uncertain, the potentiality of adverse effects arising from it is hardly subject to dispute (Marelli et al. 2011; Khanna and Crago 2012).

5. Conclusion

The main findings and highlights of this study can be summarized as follows:

- A methodological framework was presented in order to assess the cascading environmental consequences a change in crop yield and chemical composition (triggered by an increase in atmospheric [CO_2]) can have for pig feed formulation, including land use change consequences;
- Due to changes in biochemical crop composition, pig feed grown under an elevated [CO_2] would contain more soy (ca. 20%) and less wheat (ca. 5%), in comparison with today's feed.
- The positive environmental effect of elevated [CO_2] on crop yield (carbohydrates) was counter-balanced by a need for increased soy content in pig feed, and the land use consequences this generated;
- The four most important environmental impact categories in pig feed production under current and future atmospheric [CO_2], as determined by the monetized normalization methodology of Stepwise 2006 were human toxicity in terms of non-carcinogenic toxicity and respiratory inorganics, nature occupation and global warming;
- Since the protein crops (soy, rape and sunflower) account for about 60% of the overall environmental impact of pig feed, it is important, in the perspective of a future with expected growing demands for food and bioenergy (and thus for land), to optimize their supply in feed as well as their amino acids profiles (rather than their content in total protein).

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