Greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels

- according to the Directive 2009/28/EC of the European Parliament on the promotion of the use of energy from renewable sources

31/08/2010 - Revised version

28/07/2015 - Updated

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PREFACE to the 2010 revised version

This report has been produced on a request from February 22nd 2010 by the Danish Ministry of Food, Agriculture and Fisheries, with whom the Faculty of Agricultural Sciences at Aarhus University (DJF) has a contract on provision of research-based public-sector consultancy.

DJF was requested to produce a report that was structured in a similar way as the Swedish report on the same subject on describing greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure (Ahlgren et al., 2009).

The first version of the report (entitled: "Greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels and from production of biogas from manure") was finalized on June 15th 2010 and sent to the Danish Ministry of Food, Agriculture and Fisheries. Later, on August 20th 2010, The Faculty of Agricultural Sciences received a forwarded response in the form of an EU Pilot stating:

"*We are writing to you with respect to the report you submitted under Article 19(2) of Directive 2009/28/EC (1) for which we would like to thank you. However, we have now reviewed the report and it appears that some further elements are needed to comply with the requirements set out in the Directive. The following points need further clarifications:*

- *The report introduces a reference case which is not according to IPCC Tier1 methodology, where the "background" emissions are already deducted (see footnote 7 of chapter 11 of the IPCC guidelines for National GHG inventories). The revision of the report shall exclude the subtraction of a reference when IPCC Tier1 methodology is applied.*
- *The calculations include crop drying, which shall be excluded in the "cultivation step".*
- *The high SOC content in cropland in Nordjylland is likely to influence the N_2O emissions from that region. Please provide a discussion on the extent that the high SOC content influences emissions from cultivation.*
- *The inclusion of GHG emissions values for biogas from manure is not necessary, as this is considered waste, and thus bears no emissions from the point of collection.*

In the light of the above, we would be grateful if you could ask the competent authorities to respond to the above mentioned points at your earliest convenience and not later than 6 weeks of receipt of this letter."

The Faculty of Agricultural Sciences was requested by the Danish Ministry of Food, Agriculture and Fisheries to revise the report and submit the revised version by September 1st 2010. The present revised version was finalized on August 31st 2010.

In addition to the suggestions from the EU Pilot, the report has been updated and further qualified using new data available from Statistics Denmark now with area data and crop yields including 2009 and also using new statistics on the application of lime in Danish agriculture from Knowledge Centre for Agriculture, the Danish Agricultural Advisory Service (DAAS).

The first as well as the revised version of the report were authored by senior scientist Lars Elsgaard, DJF, and reviewed by research professor Jørgen E. Olesen and Head of Research Unit, John E. Hermansen, DJF.

PREFACE to the 2015 updated version

DCA – Danish Centre for Food and Agriculture was requested on April 13th 2015 by the Danish Ministry of Food, Agriculture and Fisheries to provide an updated version of the report: *Greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels - according to the Directive 2009/28/EC of the European Parliament on the promotion of the use of energy from renewable sources 31/08/2010 - Revised version.*

This aligns with the recommendations put forward in the report of 2010 where it was explicitly stated that the presented estimates should be updated with regular intervals, to account for effects of technological developments in the agricultural sector (e.g., in the sector of fertilizer production or crop varieties), better knowledge on GHG emission factors (especially for nitrous oxide emissions from soil) and/or updated interpretations of the EU Directive 2009/28/EC.

The present updated report is authored by Associate Professor Lars Elsgaard, Department of Agroecology, Aarhus University, after discussions and coordination with Professor Jørgen E. Olesen and Head of Research Unit, John E. Hermansen, Department of Agroecology, Aarhus University.

Further, the present report is updated in accordance to comments received to a draft version by the European Commission Joint Research Centre, e.g., specifically addressing the role of organic soils in the base scenario.

SUMMARY

Greenhouse gas (GHG) emissions were calculated for cultivation of winter wheat for ethanol production and winter rapeseed for biodiesel production under Danish conditions at the NUTS 2 level. The calculations were made to comply with the requirements outlined in the EU Directive 2009/28/EC from the European Parliament (2009) but including updated data and assumptions for 2014-2015. LCA methodology and interpretations of the EU Directive 2009/28/EC were generally used according to the report of Ahlgren et al. (2009, 2011) and according to an EU Pilot received in response to the first version of the present report (see Appendix 1).

The base scenario and assumptions made, updated to the 2014-2015 situation, resulted in the following emission estimates for biofuels for winter wheat and winter rapeseed.

Region	Winter wheat (g CO_{2eq}/MJ ethanol)	Winter rapeseed (g CO_{2eq}/MJ rapeseed methyl ester)
Hovedstaden	21.1	22.6
Sjælland	18.9	21.4
Syddanmark	21.3	23.6
Midtjylland	21.8	24.0
Nordjylland	23.4	24.4

Sensitivity analyses of the cropping systems showed that the final emission results depended to a large extent on the direct (and indirect) emission factors assumed for N_2O emission from the soil. Thus, the uncertainty range reported for the IPCC N_2O emission factors (IPCC, 2006) caused the final emission results in the five Regions to vary between 11 and 49 g CO_{2eq}/MJ ethanol for winter wheat and between 13 and 51 g CO_{2eq}/MJ rapeseed methyl ester (RME) for winter rapeseed.

Likewise, the assumptions made for GHG emissions associated with production of N fertilizer had pronounced impact on the final emission results. Thus, production of mineral fertilizers using best available technology (with catalytic removal of N_2O) or novel processes may have the potential to further reduce the emission results.

The emissions calculated for the present base scenarios were similar to or lower than the emissions stated as disaggregated default values for cultivation in the Directive 2009/28/EC, i.e., 23 g CO_{2eq}/MJ ethanol for winter wheat and 29 g CO_{2eq}/MJ RME for winter rapeseed; the emissions calculated were 5-18% lower for winter wheat (except for Region Nordjylland; 2% higher) and 16-26% lower for winter rapeseed.

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1. INTRODUCTION

The EU Directive 2009/28/EC from the European Parliament (2009) concerns the promotion of the use of energy from renewable sources in the Member States. One of the purposes of the Directive is to ensure that biofuels are produced in a sustainable way, and it is stated, among others, that greenhouse gas (GHG) emission savings from the use of biofuels and bioliquids shall be at least 35% as compared to a reference fossil fuel. With effect from 2017 these requirements for GHG savings are increased to 50%. Fulfilments of the sustainability criteria are required if energy from biofuels and bioliquids are to be taken into account for (i) measuring compliance with the requirements of the EU Directive 2009/28/EC concerning national targets, (ii) measuring compliance with renewable energy obligations and (iii) eligibility for financial support for the consumption of biofuels and bioliquids.

The present reporting has been done in relation to Article 19.2 in the EU Directive 2009/28/EC, which states specifically that:

> *"[…] Member States shall submit to the Commission a report including a list of those areas on their territory classified as level 2 in the nomenclature of territorial units for statistics (NUTS) […] where the typical greenhouse gas emissions from cultivation of agricultural raw materials can be expected to be lower than or equal to the emissions reported under the heading 'Disaggregated default values for cultivation' in part D of Annex V to this Directive, accompanied by a description of the method and data used to establish that list. That method shall take into account soil characteristics, climate and expected raw material yields"*

For Danish conditions it was considered that wheat ethanol, rapeseed biodiesel (rapeseed methyl ester, RME) and biogas from manure would be the major relevant production pathways of those listed in part D of Annex V to the EU Directive 2009/28/EC. Yet, concerning the production of biofuel from manure, the EU Pilot File ref n°: 1322/10/ENER (Appendix 1) stated that: "*The inclusion of GHG emissions values for biogas from manure is not necessary, as this is considered waste, and thus bears no emissions from the point of collection*". Therefore, it was chosen to exclude further calculation for biofuels from manure and the reporting is aiming at the pathways of biofuel production from winter wheat and winter rapeseed.

In the EU Directive 2009/28/EC, the typical disaggregated GHG emissions from cultivation of agricultural raw materials (e_{ec}), as listed in part D of Annex V to the Directive, are 23 g CO_{2eq}/MJ for wheat ethanol and 29 g CO_{2eq}/MJ for rapeseed biodiesel (European Parliament, 2009).

The results presented in the report are derived from LCA practices, which have a range of embedded uncertainties. Therefore, sensitivity analyses were made in order to evaluate the effect of the assumptions made. It is imperatively recommended that the present estimates should be updated with regular intervals, to account for effects of technological developments in the agricultural sector (e.g., in the sector of fertilizer production or crop varieties), better knowledge on GHG emission factors (especially for nitrous oxide emissions from soil) and/or updated interpretations of the EU Directive 2009/28/EC.

2. METHODOLOGY

The present task was to calculate the typical greenhouse gas emissions from cultivation of agricultural raw materials (e_{ec}), and compare this to the disaggregated default values for cultivation, according to the stipulations in the Directive 2009/28/EC. However, as also recognized by Ahlgren et al. (2009, 2011), the Directive contains relatively little information on the methodology for calculation of greenhouse gas emissions from cultivation of crops for biofuel production. Therefore interpretations of the directive were sometimes necessary. As far as possible the present interpretations were done in accordance with the work of Ahlgren and colleagues (2009). This work was based an extended working process and several discussions with reference group members, the Swedish Ministry of Agriculture and experts from IPCC.

Regarding the methodology presented in the EU Directive 2009/28/EC the following requirements are central to the calculations of e_{ec}:

- Emissions from the extraction or cultivation of raw materials, e_{ec}, shall include emissions from the extraction or cultivation process itself; from the collection of raw materials; from waste and leakages; and from the production of chemicals or products used in extraction or cultivation. Capture of CO_2 in the cultivation of raw materials shall be excluded. Certified reductions of greenhouse gas emissions from flaring at oil production sites anywhere in the world shall be deducted. Estimates of emissions from cultivation may be derived from the use of averages calculated for smaller geographical areas than those used in the calculation of the default values, as an alternative to using actual values. *[Annex V, Part C, Point 6]*

- Greenhouse gas emissions from fuels, E, shall be expressed in terms of grams of CO_2 equivalents per MJ of fuel, g CO_{2eq}/MJ. *[Annex V, Part C, Point 2]*

- Emissions from the manufacture of machinery and equipment shall not be taken into account. *[Annex V, Part C, Point 1]*

- The greenhouse gases to be taken into account are CO_2, N_2O and CH_4, and for calculation in terms of CO_2 equivalences those gases shall be valued as follows CO_2: 1; CH_4: 23 and N_2O: 296. *[Annex V, Part C, Point 5]*

- Where a fuel production process produces, in combination, the fuel for which emissions are being calculated and one or more other products (co-products), greenhouse gas emissions shall be divided between the fuel or its intermediate product and the co-products in proportion to their energy content (determined by lower heating value in the case of co-products other than electricity). *[Annex V, Part C, Point 17]*

- Wastes, agricultural crop residues, including straw, bagasse, husks, cobs and nut shells, and residues from processing, including crude glycerine (glycerine that is not refined), shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials. *[Annex V, Part C, Point 18]*

Additional requirements for the reporting were that the results should (as far as possible) be representative for the situation in 2010 and take into account specific conditions at the NUTS 2 level. For critical assumption this has now been updated to 2014-2015. Input data to fulfil these requirements were mainly obtained from Statistics Denmark and from specifically requested data from the Department of Agroecology and Environment, Aarhus University (provided by senior scientist Christen D. Børgesen and academic employee Inge T.

Kristensen). Base scenarios were calculated for crops fertilized with commercial fertilizers, whereas the effect of slurry application was addressed in the sensitivity analyses. The base scenario was calculated for commercial fertilizers as cropping systems for energy crops are usually not tightly coupled to animal husbandry (Elsgaard et al., 2013).

As discussed by Ahlgren et al. (2009), it was not initially clear whether crop drying should be taken into account in the calculation of e_{ec}. However, in the present context this has been clarified by the EU Pilot File ref n°: 1322/10/ENER (Appendix 1) stating that: "…*crop drying […] shall be excluded in the "cultivation step"*. This suggestion has been followed in the present report.

Further, as also discussed by Ahlgren et al. (2009), calculations of N_2O emissions from crop cultivation could be based on a comparison between crop cultivation and extensive grasslands as reference systems, implying that background emissions from the extensive grasslands should be subtracted as "background" emissions. However, as outlined in the EU Pilot File ref n°: 1322/10/ENER (Appendix 1) the use of IPCC Tier 1 methodology to calculate the N_2O emission implies that "…*the "background" emissions are already deducted…*". The present report therefore excludes the subtraction of a reference as the IPCC Tier 1 methodology is applied – both for calculations of direct and indirect N_2O emissions.

As an expansion of the parameters considered by Ahlgren et al. (2009), irrigation, which may be important on sandy Danish soils, were included in the calculations. Likewise, the emissions associated with liming were included as liming belongs to normal agricultural practice on Danish soils.

Data on the average GHG emissions from production and distribution of electricity in Denmark in 2014 was obtained from Energinet.dk (2015). According to Energinet.dk (2015) the loss in the distribution net is not included in the environmental declaration, but can be accounted for by an average loss value of 5%. A resulting value of 307 g CO_{2eq}/kWh was then used for electricity in Denmark.

3. INPUT DATA FOR CULTIVATION OF CROPS FOR BIOFUEL PRODUCTION

3.1 Cultivated areas and yields at the NUTS 2 level

Denmark is currently represented by five administrative Regions that were created as part of the Danish Municipal Reform in 2007 to replace the former thirteen counties. The five new Regions correspond to the NUTS 2 level in the Nomenclature of Territorial Units for Statistics (Fig. 1). Data on agricultural land use from Statistics Denmark are presently available on the NUTS 2 level from the years 2006-2014. These available data for cultivated areas and yields of winter wheat and winter rapeseed were used in the present report to calculate an estimate of the 2015 situation by calculating the arithmetic mean (Table 1 and 2). Yearly increases in yield, as historically evidenced, were considered to be of marginal importance as yields under Danish conditions have showed a stagnant tendency during the last decade, especially for winter wheat (Petersen et al., 2010).

Figure 1. The five Danish Regions that represents the NUTS 2 level: Hovedstaden, Sjælland, Syddanmark, Midtjylland and Nordjylland.

Table 1. Cultivated area of winter wheat and winter rapeseed in the five Danish Regions (1000 ha). Data are mean and standard deviation (std dev) from 2006-2014. Source, Statistics Denmark (2015a)

Region	Winter wheat (x 1000 ha)		Winter rapeseed (x 1000 ha)	
	mean	std dev	mean	std dev
Hovedstaden	28.1	2.5	7.4	1.3
Sjælland	150.5	11.0	34.2	8.1
Syddanmark	182.2	21.9	46.1	7.8
Midtjylland	177.3	20.7	43.0	5.7
Nordjylland	124.3	17.1	26.7	2.8

Table 2. Yield of winter wheat and winter rapeseed in the five Danish Regions (hkg/ha). Standardized to 15% moisture content for winter wheat and 9% moisture content for winter rape seed. Data are mean and standard deviation (std dev) from 2006-2014. Source, Statistics Denmark (2015a)

Region	Winter wheat (hkg/ha)		Winter rapeseed (hkg/ha)	
	mean	std dev	mean	std dev
Hovedstaden	71.6	6.4	37.1	4.4
Sjælland	80.5	7.6	39.5	4.1
Syddanmark	72.8	6.4	36.8	3.2
Midtjylland	70.8	5.3	35.9	3.7
Nordjylland	66.9	5.9	35.1	3.8

3.2 Seed rate

Under Danish conditions winter wheat is preferably established in mid-September at a plant density of 290 plants per m^2 as recommended, e.g., by the Danish Agricultural Advisory Service (DAAS, 2008a). This corresponds to a seed rate of 148 kg/ha assuming a field emergence of 90% and a weight 46 g per 1000 kernels. Winter rapeseed is best established in mid-August at a seed rate of 5 kg/ha (DAAS, 2008b). To account for the impact of these seed rates, they were subtracted from the yield data in the further calculations, except for the calculation of residues (22% of above-ground biomass), where total yields were included.

3.3 Fertilizer application

Fertilizer N application rates (Table 3) were adapted from the standards in the Ministerial guidance on fertilization and harmony rules (Ministry of Food, Agriculture and Fisheries, 2015). Guiding standards for phosphorous (P) and potassium (K) were likewise included in the calculations according to the Ministry of Food, Agriculture and Fisheries (2015):

winter wheat:	19 kg P/ha and 71 kg K/ha
winter rapeseed:	26 kg P/ha and 82 kg K/ha

Table 3. Danish nitrogen standards (kg N/ha) for 2014/2015 (Ministry of Food, Agriculture and Fisheries, 2015)

Crop	Nitrogen standards for different soil types (kg N/ha)				
	Coarse sand JB 1+3	Fine sand JB 2+4 & 10-12[a]	Irrigated sandy soil JB 1-4	Sandy loam JB 5-6	Loamy soils JB 7-9
Winter wheat	133	138	156	156	167
Winter rapeseed	165	175	175	181	183

[a] JB 10-12 soils represent silt, humus and special soil types

The definition of soil types in the nitrogen standards relates the Danish JB soil classification system which divides soils into types from JB 1 to JB 12. To calculate the average fertilizer application in each Region, the distribution of crops and irrigation on different soil types was analysed with data obtained from the Department of Agroecology, Aarhus University (Inge T. Kristensen, personal communication). The data compiled represented an estimate of the situation in 2007, and based on the total cropping areas in 2007 and 2015, the data were recalculated to represent the 2015 situation (Table 4 and 5).

Table 4. Area estimates (ha) of soil types cropped with winter wheat in 2015 in each of the five Regions. Estimates are the total areas and areas with irrigation (irrigt) for each soil type

Soil type	Hovedstaden		Sjælland		Syddanmark		Midtjylland		Nordjylland	
	total	irrigt	total	irrigt	total	irrigt	total	irrigt	total	irrigt
JB 1	68	0	552	41	19439	13010	22483	13602	6818	2654
JB 2	200	35	1368	137	1159	333	7396	3643	38442	15191
JB 3-4	7105	812	19863	2678	46844	17827	73444	22225	46487	14571
JB 5-6	13366	928	88924	8557	93059	14922	56000	9075	15567	3255
JB 7	6637	162	35322	2566	14054	2452	8562	1067	5709	1360
JB 8-10	161	0	853	58	2997	1087	1766	551	1257	215
JB 11	525	106	2801	819	4570	2625	6333	3227	9372	4643
JB 12	39	9	819	199	79	29	1317	583	649	160
SUM	28100	2051	150500	15055	182200	52285	177300	53972	124300	42049

Table 5. Area estimates (ha) of soil types cropped with winter rapeseed in 2015 in each of the five Regions. Estimates are total areas and areas with irrigation (irrigt) for each soil type

Soil type	Hovedstaden		Sjælland		Syddanmark		Midtjylland		Nordjylland	
	total	irrigt	total	irrigt	total	irrigt	total	irrigt	total	irrigt
JB 1	44	3	80	17	6943	4394	7287	4053	2359	886
JB 2	63	13	294	58	389	132	2261	1021	10198	4062
JB 3-4	3553	449	6243	942	13245	4779	20192	5692	10300	3224
JB 5-6	2644	277	21263	2131	21191	3421	11085	1750	2191	508
JB 7	931	51	5403	549	2704	335	1307	190	537	80
JB 8-10	9	0	166	0	523	197	98	12	63	23
JB 11	153	45	737	206	1095	644	751	418	939	538
JB 12	4	1	15	1	9	5	19	8	113	53
SUM	7400	838	34200	3903	46100	13907	43000	13144	26700	9372

Soil classes for the N standards and the area estimates (Table 3 to 5) were not completely overlapping. Therefore, three assumptions were made: (i) the area fertilized according to JB 7-9 standards was estimated as the cropping area on JB 7-10, (ii) the area fertilized according to JB 10-12 standards was estimated as the cropping area on JB 11-12, and (iii) an average nitrogen standard was used for the non-irrigated JB 1-4 soil types (135.5 kg N/ha for winter wheat and 170 kg N/ha for winter rapeseed). As the share of JB 8-10 areas is very minor, the impact of the assumptions was considered to be negligible, but allowed an assessment of the mean application of fertilizer-N in the five Regions (Table 6).

Table 6. Mean application rate of fertilizer-N estimated for each of the five Regions (kg N/ha)

Region	Winter wheat (kg N/ha)	Rapeseed (kg N/ha)
Hovedstaden	154	176
Sjælland	156	179
Syddanmark	152	179
Midtjylland	148	177
Nordjylland	145	173

3.4 Greenhouse gas emissions associated with fertilizer production

Greenhouse gas emissions associated with fertilizer production vary according to, e.g., different processing technologies, energy sources and utilization of co-products (Wood and Cowie, 2004; Cherubini, 2010). New technologies, including catalytic cleaning of N_2O, has lowered the emissions from production of fertilizers over the last decade, and therefore the average European emission estimate of 6.8 kg CO_{2eq}/kg N by Jenssen and Kongshaug (2003), was considered already by Ahlgren et al. (2009) to represent a ‘worst case’ scenario. Based on recent data from the dominant producer (Yara) on the Swedish market, Ahlgren et al. (2009) adopted the estimate that the emissions of greenhouse gases during production of nitrogen fertilizers for Sweden would on average be 2.9 kg CO_{2eq}/kg N in 2010.

On the Danish market, Yara has a major position that can be estimated to ca. 60% of the market share (Lars Johansen, personal communication). At the same time, Yara from 2010 guarantees an environmental load of less than 4 kg CO_{2eq}/kg N for fertilizers produced for Denmark, Finland, Norway and Sweden (Yara, 2010). This figure is set as a maximum, and a value of 3.52 kg CO_{2eq}/kg N was considered to be a realistic average carbon footprint for Yara fertilizers supplied to Denmark in 2010 (Jenssen, 2010). Yet, due to continued focus on reducing carbon footprints from fertilizer production the average carbon footprint for Yara fertilizers supplied to Denmark in 2014 was lowered to 3.1 kg CO_{2eq}/kg N (Fossum, 2014).

For the rest of the Danish market (ca. 40% of the market share) different European producers from, e.g., the Netherlands and Germany are involved. For this market share, certified carbon footprint data from major suppliers like Eurochem Agro GmbH (Germany) and OCI Nitrogen B.V. (The Netherlands) points to similar carbon footprints as achieved for Yara, thus demonstrating an overall improvement of GHG emissions obtained by European producers in recent years (Börjesson and Tufvesson, 2011). Since Yara is a market leading supplier of N fertilizers to the Danish market, it was assumed that competitors eventually will have to comply with the standards set by Yara. Therefore a contemporary estimate of greenhouse gas emissions associated with production of ammonium-nitrate-based fertilizers for the Danish market in 2015 was set to be 3.1 kg CO_{2eq}/kg N (Fossum, 2014).

Emission values for production of phosphorous (P) and potassium (K) were adopted from LowCVP (2004). The values used were 0.71 kg CO_{2eq}/kg P and 0.46 kg CO_{2eq}/kg K.

The emissions associated with transport of fertilizers to Denmark were tentatively estimated by considering a route involving 1000 km of sea freight and 350 km of road transportation. These distances were considered to be within a realistic range although detailed assessments were not performed. Emissions of greenhouse gas equivalents associated with transport were derived from the LCA Food database (Nielsen et al., 2003) and the values used were 8.99 g CO_{2eq}/ton/km for sea freight and 227 g CO_{2eq}/ton/km for road transportation by truck. The contribution from transport was in the range of 3-4% of the emissions calculated for production of fertilizers.

3.5 Pesticides

For the application of pesticides, no detailed statistic were available that specified the amount of active substance given to individual crops in each of the five Regions. However, according to Statistics Denmark (2015b) the average amount of active substance per treatment in Danish agriculture corresponded to 0.60 kg/ha in 2007-2012. This value was used in the present calculations.

To estimate the greenhouse gas emissions from the production of chemical pesticides, data from Olesen et al. (2004) were used (Table 7).

Table 7. Emission of greenhouse gases from production of pesticides (Olesen et al., 2004)

Greenhouse gas	Emission (kg/kg active substance)
CO_2	4.92
CH_4	0.00018
N_2O	0.0015

3.6 Field operations

The type and number of field operations assumed for cultivation of winter wheat and winter rapeseed were adapted from the Danish Agricultural Advice Service (DAAS, 2009a). All regions were assumed to have the same type and number of field operations (Table 8).

Table 8. Field operations during cultivation of winter wheat and rapeseed (DAAS, 2009a), and diesel consumption associated with field operations (Dalgaard et al., 2004)

Operation	Frequency		Diesel consumption
	Winter wheat	Winter rapeseed	
Ploughing	1	1	23 L/ha
Stubble-harrowing	0	1	7 L/ha
Fertilizing	2	2	2 L/ha
Combined sowing/harrowing	1	1	~5 L/ha
Rolling	1	1	2 L/ha
Application of pesticides	3	3	1.5 L/ha
Threshing	1	1	14 L/ha

The quantity of lubrification oil consumed was rated to 0.7% of the diesel consumed and the emission associated with production of lubrification oil was assumed to be the same as for diesel oil (Bernesson et al., 2006).

To account for differences in energy needed for soil operations on different soil types, the diesel consumption for ploughing, stubble-harrowing, combined sowing/harrowing and rolling was multiplied by 1.1 for calculations on clay soils and organic soils (>JB no. 7) and by 0.9 for calculations on sandy soils (here JB no. 1-4) as suggested by Dalgaard et al. (2004).

To estimate the energy needed for field operations in each Region, calculations were done on the basis of the cropping area estimates for different soil types in the five Regions as presented in Table 4 and 5. The standard value used for the indirect and direct GHG load of diesel consumption was 3.36 kg CO_{2eq}/L (Nielsen et al., 2003).

3.7 Liming

The GHG effect of liming (used to increase soil pH) was included in the calculations. As no statistics were available for the Region-, soil type-, or crop-specific use of lime, an average estimate was made from available data on the total use of lime in Danish agriculture during the last 10 years (SEGES, 2015) as shown in Table 9. Thus, data on the mean lime use during 2005-2014 was combined with data on the cultivated area to provide an estimate of the area-specific use of agricultural lime (170 kg/ha). Direct emissions from lime application were calculated according to IPCC (2006) using the emission factor (EF) for limestone of 0.12. The GHG emission associated with excavation and transport was estimated to 19 g CO_{2eq}/kg according to Hvid (2009). Consumption of diesel during the field operation of liming was assumed to be 1.5 L/ha (Dalgaard et al., 2004).

Table 9. Total use of lime for agricultural purposes in Denmark in 2005-2014 (SEGES, 2015)

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean
Total lime use (1000 t $CaCO_3$)	497	438	434	518	410	345	366	426	552	538	452

3.8 Irrigation

Precipitation in Denmark may have a considerable year-to-year variation as well as a geographical variation. The typical range is between 600 to 900 mm of precipitation. Due to the prevalence of sandy soils in the western part of the country, these areas have the highest and most frequent need for irrigation in periods of drought. The crop-specific requirements for irrigation on sandy soils (here JB nr. 1-4) are assumed to be 80 mm/ha for winter wheat and 125 mm/ha for winter rapeseed (Mogensen and Jensen, 2002). For the remaining soil types the need for irrigation is lower and more infrequent than for the sandy soils. In the present calculations it was assumed that irrigation on these soil types generally represented one third of the value for sandy soils.

Irrigation is generally accomplished by self-moving systems with water pumping comprising the main energy consumption. It was assumed that water pumping was driven by electricity and the energy consumption for irrigation was taken to be 4.6 kWh/mm/ha (Refsgaard et al., 1998; Jens J. Høy, personal communication). Thus, in terms of GHG emissions associated with use of electricity, irrigation corresponded to 1.41 kg CO_{2eq}/mm/ha as calculated for electricity supplied in Demark.

To calculate the energy needed for irrigation in each of the five Regions, calculations were done on the basis of the area estimates for irrigation presented in Table 4 and 5.

3.9 Nitrous oxide emissions from cultivation

Nitrous oxide is formed in soil mainly as a result of microbial nitrification and denitrification activity (Sahrawat and Keeney, 1986). The potential of a soil to form and emit N_2O increases with increasing N availability, but other major controllers of the N_2O production also exist, such as oxygen status, temperature and soil pH (e.g., Granli and Bøckman, 1994). It is generally observed that the production and emission of N_2O is highly variable in time and space and it is challenging, therefore, to model and predict the N_2O emission from agricultural cropping systems (Vinther and Hansen, 2004).

In the present assessment, nitrous oxide emissions from cultivation of winter wheat and winter rapeseed were calculated according to the Tier 1 methodology of IPCC (2006), which is intended for national greenhouse gas inventories. The method includes a direct contribution from N_2O produced from added N in the soil system and an indirect contribution of N_2O produced from N that escapes the cropping system via leaching and volatilization. For the latter (the indirect emission) a disaggregated approach was adopted as used in Danish national emission inventories (Nielsen et al., 2013). This approach differentiates between the amount of leachate N below the root zone, and the amount eventually reaching rivers and estuaries.

Direct N_2O emission in the IPCC (2006) methodology is calculated from the empirical assumption that 1% of the added nitrogen in soil system is emitted as N_2O. To calculate the amount of added nitrogen, the IPCC methodology includes the amount of fertilizer N applied and a contribution from above-ground and below-ground crop residues:

$N_2O\ (direct) = (F_{SN} + F_{ON} + F_{CR}) \times EF_N \times 44/28\ (kg\ N_2O/ha)$, where:

F_{SN} = Amount of synthetic fertilizer applied (kg N/ha)
F_{ON} = Amount of manure applied (kg N/ha)
F_{CR} = Amount of N in crop residues above ground and below-ground (kg N/ha)
EF_N = IPCC emission factor for added nitrogen (0.01 kg N_2O-N/kg N)

Estimates for the amount of N in crop residues were calculated according to Mikkelsen et al. (2006), including contributions from stubble, chaff and non-salvaged straw. The percentage of the cropped area with non-salvaged straw (Table 10) was calculated as the average of data from 2006-2014 (Statistics Denmark, 2015c). Values assumed for the amount of straw yield relative to grain yield and the N content in straw of winter wheat and winter rapeseed are shown in Table 11. The amount of below-ground crop residues was estimated to 22% of the aboveground biomass (i.e., yield + straw + stubble/chaff) and the N content of below-ground residues was estimated to 0.9% (IPCC, 2006)

Organic soils are treated separately by IPCC (2006) applying a fixed emission factor of 8 kg N_2O-N ha^{-1}. However, the definitions of organic soils in the Danish JB system and the IPCC guidelines for calculation of N_2O emission are different: In the Danish system soils classify as JB 11 (organic) if they have a C content higher than 6% (equivalent to a humus content of 10%), whereas in the IPCC definition (IPCC, 1996) soils should have a C content higher than 20% (equivalent to a humus content of 35%) to be regarded as organic.

Novel soil mapping in Denmark shows that the current Danish area with >6% C (JB 11) is 114271 ha, the area with >12% C is 70481 ha, and the area with >24% C is 37551 (Greve et al., 2012; 2014); an interpolated estimate of the area with >20% C is 48531 ha. This means that (100*48531/114271) 43% of the JB11 area would classify as organic soils in relation to the use of IPCC emission factors for organic soils. Based on this estimate, and the NUTS 2 cropping areas on JB 11 soils (Table 4 and 5) the additional contribution of organic soils in N_2O emissions were included according to IPCC (2006).

Table 10. Percentage of cropped area with non-salvaged straw (%). Mean values for 2006-2014. Calculated from data in Statistics Denmark (2015c)

Region	Winter wheat	Winter rapeseed
	Mean (%)	Mean (%)
Hovedstaden	53	93
Sjælland	37	82
Syddanmark	36	76
Midtjylland	40	78
Nordjylland	45	79

Table 11. Parameters included to calculate the direct N_2O emission from crop residues. Data from Statistics Denmark (2015c) and Swedish Environmental Protection Agency (2007)

Parameter	Winter wheat	Rapeseed
Salvageable straw (DM) relative to harvested grains	0.55	0.90
N content in straw (% of DM)	0.51	1.07

Indirect nitrous oxide emissions are calculated from the nitrogen lost by leaching and volatilization. Leaching losses were estimated for each crop and Region (Table 12) based on data from Department of Agroecology and Environment, Aarhus University, using the model tool N-LES4 (Kristensen et al., 2008; Børgesen et al., 2009; Christen D. Børgesen, personal communication). No deductions were made for leaching of nitrogen deposited via air pollution. To calculate the contribution of N_2O from the amount of leached N, the IPCC (2006) disaggregated emission factors were applied according to 0.0025 kg N_2O-N/kg N (groundwater and surface drainage), 0.0025 kg N_2O-N/kg N (rivers) and 0.0025 kg N_2O-N/kg N (estuaries). Based on Nielsen et al. (2013) disaggregated Danish national data for N leaching to groundwater, rivers and estuaries during 1990-2009 show that total N leaching (average) is 199 Gg to groundwater, 88 Gg to rivers and 38 Gg to estuaries. Hence, the proportion of N leaching to groundwater that is transmitted to rivers and estuaries is 44% and 35% respectively. This means that the combined emission factor for N leaving the root zone is estimated as (0.0025*100%) + (0.0025*44%) + (0.0025*38%) = 0.0046.

Table 12. Estimated average leaching losses out of the root zone from winter wheat and winter rapeseed (kg N/ha/year). Data for the Danish counties from 2005 were recalculated on area basis to represent the new Regions.

Region	Winter wheat	Rapeseed
Hovedstaden	50	44
Sjælland	48	42
Syddanmark	74	66
Midtjylland	75	66
Nordjylland	68	61

Nitrogen lost through volatilization of ammonia was assumed to be 2.2% of the mineral fertilizers applied (Mikkelsen et al., 2006). This percentage is considered to be realistic (or even high) for Danish conditions although the IPCC (2006) default value is somewhat higher (10% of applied N). The discrepancy is mainly due to the fact that the IPCC estimate is an average value for different fertilizer types including urea, which has a high ammonia emission, but which is relatively unimportant in Denmark (Mikkelsen et al., 2006). To calculate the contribution of N_2O from the amount of volatilized NH_3 the IPCC (2006) emission factor of 0.01 kg N_2O-N/kg NH_3-N was applied.

In summary, indirect nitrous oxide emissions (kg N_2O/ha) were calculated as:

$N_2O\ (indirect) = [\Sigma(F_L \times EF_L)_c + (F_A \times EF_D)] \times 44/28,$ where:

F_L = Amount of nitrogen lost through N leaching to compartments (c) below the root zone, in rivers and in estuaries, respectively (kg N/ha)
EF_L = IPCC emission factor for leached nitrogen (0.0025 kg N_2O-N/ha)
F_A = Amount of ammonia emitted from mineral fertilizer application
EF_D = IPCC emission factor for volatilization and re-deposition (0.01 kg N_2O-N/kg NH_3-N)

3.10 Energy balance and allocation

The Directive 2009/28/EC (Annex V, Part C, Point 2) states that GHG emissions from fuels shall be expressed in terms of grams of CO_2 equivalent per MJ of fuel. Also, it states (Annex V, Part C, Point 17) that *"where a fuel production process produces, in combination, the fuel for which emissions are being calculated and one or more other products (co-products), greenhouse gas emissions shall be divided between the fuel or its intermediate product and the co-products in proportion to their energy content (determined by lower heating value in the case of co-products other than electricity"*. Therefore, for the final calculations of the emission results, energy balance and allocations were included as described below.

Calculations of energy balance for winter wheat were based on the estimates that 1 L of pure ethanol is produced from 2.65 kg wheat (Bernesson et al., 2006) and that the energy content of ethanol (the lower calorific value) is 21 MJ/L (Directive 2009/28/EC, Annex III). Thus, the energy content per unit mass was calculated to 7.92 MJ/kg.

Production of ethanol generates the by-product distiller's waste, which is usually used for animal feed. Therefore, the environmental load of the production process is shared between ethanol and distiller's waste by allocation. In the present calculations this was done according to Bernesson et al. (2006), who calculated a share for ethanol of 60.8% based on the two product's total energy yield. In the case of winter rapeseed, it was assumed that 1 kg rapeseed corresponded to 16.3 MJ RME (Ahlgren et al., 2009). For the allocations, the environmental load was shared between RME, rapemeal and glycerine. The share allocated to RME was 64.4% based on the three product's total energy yield (Bernesson et al., 2004).

Based on these estimates of energy balance and allocation, the final emission results were calculated as:

$$\textit{Emission result (g } CO_{2eq}\textit{/MJ)} = \frac{Emission\ (g\ CO_{2eq}/ha) \times allocation\ \ factor}{Crop\ \ yield\ (kg/ha) \times\ fuel\ energy\ obtained\ (MJ/kg)}$$

4. RESULTS

4.1 Greenhouse gas emissions from cultivation of crops for biofuel production

Based on the input data in Chapter 3, the emission of greenhouse gases from cultivation of winter wheat and winter rapeseed was calculated in the units of both g CO_{2eq}/ha and g CO_{2eq}/MJ fuel (Table 13-16). The total emission estimates ranged from 18.6 to 23.0 g CO_{2eq}/MJ ethanol for winter wheat (Table 14) and from 21.4 to 24.4 g CO_{2eq}/MJ RME for winter rapeseed (Table 16). The calculations showed that the two major contributors to the final result were the direct emissions of N_2O from soil and the GHG emissions associated with fertilizer production. Direct emissions of N_2O from soil alone accounted for 48-50% of the total emission from winter wheat and 48-51% of the total emission from winter rapeseed. Differences in the GHG emissions in the five Regions were less than 77 g CO_{2eq}/ha (< 3.5%) for both cropping systems with the highest emissions for wheat in Region Nordjylland and the highest emissions for rapeseed in Region Syddanmark (Table 13 and 15).

Table 13. Emission of GHG from cultivation of winter wheat (kg CO_{2eq}/ha)

Region	Field operations	Irrigation	Liming	Fertilizer production and transport	Pesticide production	Direct N_2O emission from soil	Indirect N_2O emission	Total (kg CO_{2eq}/ha)
Hovedstaden	184	5	78	545	9	985	125	1931
Sjælland	185	5	78	552	9	996	121	1946
Syddanmark	181	25	78	539	9	974	177	1983
Midtjylland	179	29	78	526	9	973	179	1972
Nordjylland	178	34	78	516	9	1019	163	1998

Table 14. Emission of GHG from cultivation of winter wheat (g CO_{2eq}/MJ ethanol)

Region	Field operations	Irrigation	Liming	Fertilizer production and transport	Pesticide production	Direct N_2O emission from soil	Indirect N_2O emission	Total (g CO_{2eq}/MJ ethanol)
Hovedstaden	2.0	0.1	0.9	6.0	0.1	10.8	1.4	21.1
Sjælland	1.8	0.1	0.8	5.4	0.1	9.7	1.2	18.9
Syddanmark	2.0	0.3	0.8	5.8	0.1	10.5	1.9	21.3
Midtjylland	2.0	0.3	0.9	5.8	0.1	10.8	2.0	21.8
Nordjylland	2.1	0.4	0.9	6.1	0.1	12.0	1.9	23.4

Mainly due to differences in the yield in the five Regions (and thereby the MJ of fuel obtained), the emission results in terms of g CO_{2eq}/MJ fuel varied at up to 19% for winter wheat and 13% for winter rapeseed between the five Regions (Table 14 and 16). The highest emission results were seen for Region Nordjylland whereas the lowest emission results were seen for Region Sjælland (Table 14 and 16).

The emission results presently calculated were similar to or lower than the corresponding emissions reported as ‘disaggregated default values for cultivation’ in part D of Annex V to the Directive 2009/28/EC, which were 23 g CO_{2eq}/MJ ethanol for winter wheat and 29 g CO_{2eq}/MJ RME for winter rapeseed (European Parliament, 2009).

Table 15. Emission of GHG from cultivation of winter rapeseed (kg CO_{2eq}/ha)

Region	Field operations	Irrigation	Liming	Fertilizer production and transport	Pesticide production	Direct N_2O emission from soil	Indirect N_2O emission	Total (kg CO_{2eq}/ha)
Hovedstaden	203	14	78	627	9	1076	114	2122
Sjælland	208	10	78	636	9	1086	110	2137
Syddanmark	203	42	78	636	9	1067	163	2198
Midtjylland	199	50	78	630	9	1047	162	2175
Nordjylland	197	58	78	617	9	1054	151	2165

Table 16. Emission of GHG from cultivation of winter rapeseed (g CO_{2eq}/MJ RME)

Region	Field operations	Irrigation	Liming	Fertilizer production and transport	Pesticide production	Direct N_2O emission from soil	Indirect N_2O emission	Total (g CO_{2eq}/MJ RME)
Hovedstaden	2.2	0.2	0.8	6.7	0.1	11.4	1.2	22.6
Sjælland	2.1	0.1	0.8	6.4	0.1	10.8	1.1	21.4
Syddanmark	2.2	0.4	0.8	6.8	0.1	11.4	1.7	23.6
Midtjylland	2.2	0.5	0.9	6.9	0.1	11.5	1.8	24.0
Nordjylland	2.2	0.7	0.9	7.0	0.1	11.8	1.7	24.4

5. DISCUSSION AND SENSITIVITY ANALYSES

The results derived for GHG emissions from cultivation of agricultural crops for biofuels – as presented in Table 14 and 16 – were calculated according to a number of assumptions and interpretations of the Directive 2009/28/EC. The assumptions and interpretations were justified as described in detail in Chapter 3, but still were associated with considerable embedded uncertainties, that have to be considered in order to interpret the robustness of the results. Therefore, a number of sensitivity analyses were performed.

5.1 Diesel consumption in cultivation

The present estimate of fuel consumption related to field operations was 53-62 L of diesel per ha. This was based on estimates of diesel consumption for individual cultivation operations according to DAAS (2009a). It is generally found that the diesel consumption actually experienced may be somewhat higher than the result of these disaggregated calculations, and, for example, a diesel consumption of 97 L/ha was included in the calculations of Hvid (2009) for cultivation of winter wheat on a Danish JB 6 soil (including diesel consumption for slurry application). Dalgaard and Dalgaard (2006) presented examples of field operations for winter wheat and winter rapeseed resulting in diesel consumptions of 81-93 L/ha depending on the soil type. Using the diesel consumption estimates calculated according to Dalgaard and Dalgaard (2006) would on average increase the final emission results in Table 14 and 16 by 5.4% for winter wheat and 3.9% for winter rapeseed.

5.2 Application of slurry as fertilizer

The cultivation systems considered in the present calculations are based on application of mineral fertilizer to meet the plant requirement for major nutrients (Elsgaard et al., 2013). Use of animal slurry may substitute a part of the mineral fertilizer and thereby have an impact on the results. Considering slurry as a waste product, the Directive 2009/28/EC specifies that it shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection. However, it is not clear if the point of collection includes or excludes the management and storage in slurry tanks prior to spreading on the field. During storage in slurry tanks a notable emission of CH_4 and N_2O occur which will have a large impact on the emission results. Because of these uncertainties in relation to the Directive 2009/28/EC, Ahlgren et al. (2099) chose not to present calculations based on scenarios with slurry.

For the present purpose of testing the impact of slurry fertilization, tentative calculations were made based on the assumptions that either (i) the use of slurry was ‘free’ of emissions up to the point of collection in the storage tanks or (ii) the use of slurry was associated with N_2O and CH_4 emissions related to management and storage. To estimate the slurry emissions relative to the amount of N in the slurry the following assessment was made:

Greenhouse gas emissions from handling and storage of animal manure in Denmark in 2002 was reported to 1.95 Gg N_2O and 47.1 Gg CH_4 (Mikkelsen et al., 2006), corresponding to a total of 1.66 mio. ton CO_{2eq}. Assuming that slurry represents 83% of the total animal manure in Denmark (Petersen and Sørensen, 2008), the GHG emission from slurry was tentatively estimated to 1.38 mio. ton CO_{2eq}. Further, the total N content of animal slurry has recently been estimated to 141.731 ton N based on data from 2005 (Petersen and Sørensen, 2008). Combining these emission and N data provides an estimate of the GHG emission associated with slurry N corresponding to 9.7 kg CO_{2eq}/kg N.

The use of slurry for fertilization was considered in a scenario where the cropping systems were amended with 25 t slurry ha^{-1} corresponding to 125 kg N ha^{-1}. With an N fertilizer efficiency of 75% this corresponded to 94 kg N as mineral fertilizer. The remaining N was assumed to be supplied to the cropping systems in the form of mineral fertilizer (*cf.* Table 6). Direct and indirect N_2O emission from applied slurry N was calculated according to IPCC (2006). For the estimates of indirect N_2O emission, the default fraction (20%) of applied organic N fertilizer that volatilises as NH_3 and NO_x was used (IPCC, 2006).

Calculating the impact of slurry N on the total emissions from the cropping systems showed that emissions rather similar to the base scenario were obtained if no emission costs were attributed to handling and storage of the slurry (Fig. 2). However, if the emissions during handling and storage of the slurry were assigned to the cropping systems, a considerably higher emission result was derived than in the base scenario with mineral N (Fig. 2).

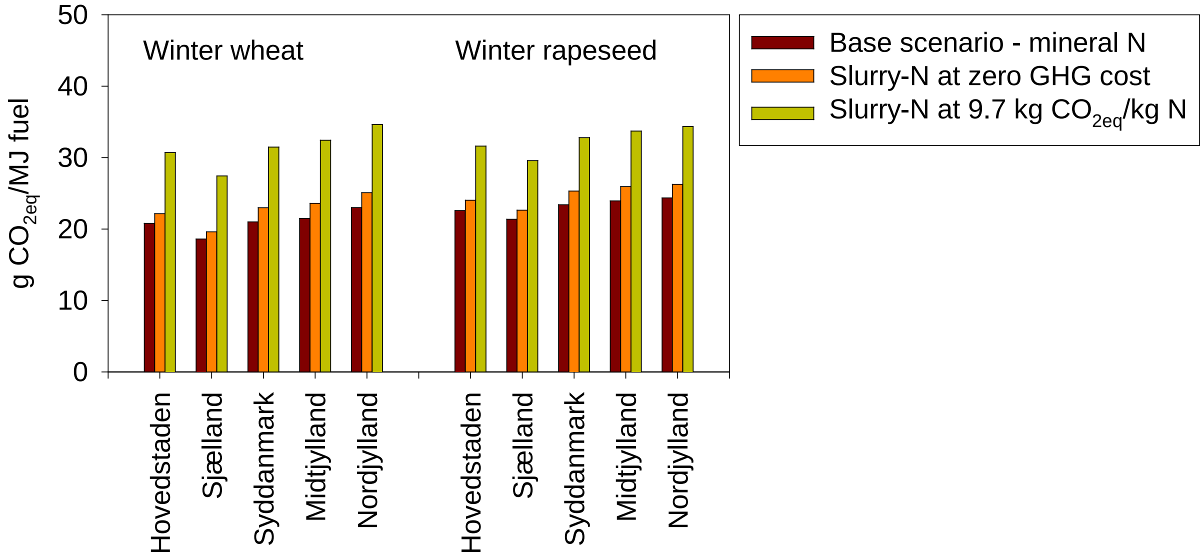

Figure 2. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed in a base scenario with mineral N fertilization and in scenarios with combined slurry (25 t/ha) and mineral N fertilization. Calculations assumed that production of slurry N was associated with GHG emissions of 0 and 9.7 kg CO_{2eq}/kg N, respectively.

An estimate of the GHG impact of cultivation of winter wheat on Danish JB 6 soil fertilized with slurry (136 kg N/ha) and mineral fertilizer (59 kg N/ha) was presented by Hvid (2009), who attributed the same GHG cost of production for slurry N as for fertilizer N (see also DAAS, 2009b). The standard value used by Hvid (2009) was 8.2 kg CO_{2eq}/kg N, and the total

GHG impact of the cropping system was found to 44.3 kg CO_{2eq}/hkg grain (Hvid, 2009). The present slurry scenario (with GHG emissions assigned to slurry N) resulted in a similar estimate of 39.1 kg CO_{2eq}/hkg grain for Region Midtjylland, which has a dominant soil type similar to that considered by Hvid (2009).

5.3 Irrigation

The need for irrigation depends on weather conditions and varies from year to year. To test the influence of the assumptions made for irrigation calculations were made based on one third and three times the need considered in the base scenarios (Fig. 3). The result of these sensitivity analyses showed that the assumptions made for irrigation had a very modest impact on the final emission results; for winter wheat the final emission results on average were within 99-103% (mean, 102%) of the base scenario and for winter rapeseed the final emission results on average were within 98-105% (mean, 103%) of the base scenario.

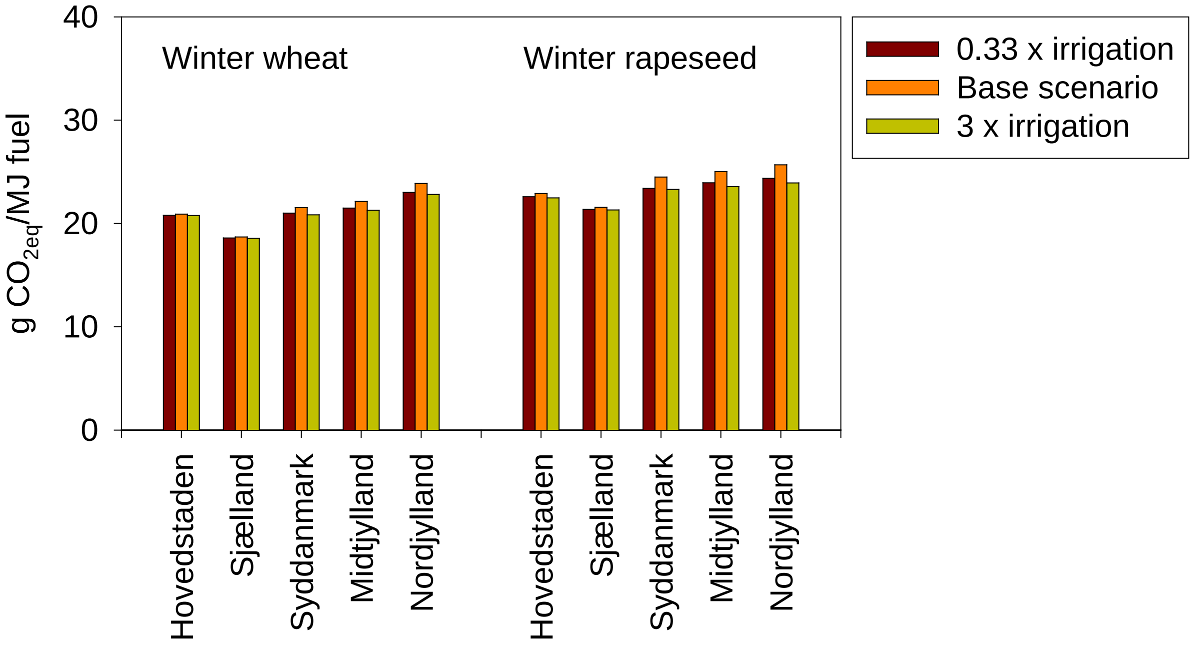

Figure 3. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed assuming different needs for irrigation corresponding to one third and three times the value used in the present base scenario calculations.

5.4 Crop yields

Data on crop yields from Statistics Denmark were reported on the NUTS 2 level from the years 2006-2014. In the present calculations the base scenario was calculated according to the average yields on the NUTS 2 level based on these data. However, the variation between yields in individual years influences the emission results as the yields are the basis for the MJ fuel obtained. The emission results according to the yield in individual years (2006, 2011 and 2014) are shown in Fig. 4, which demonstrates the importance of the yield estimates.

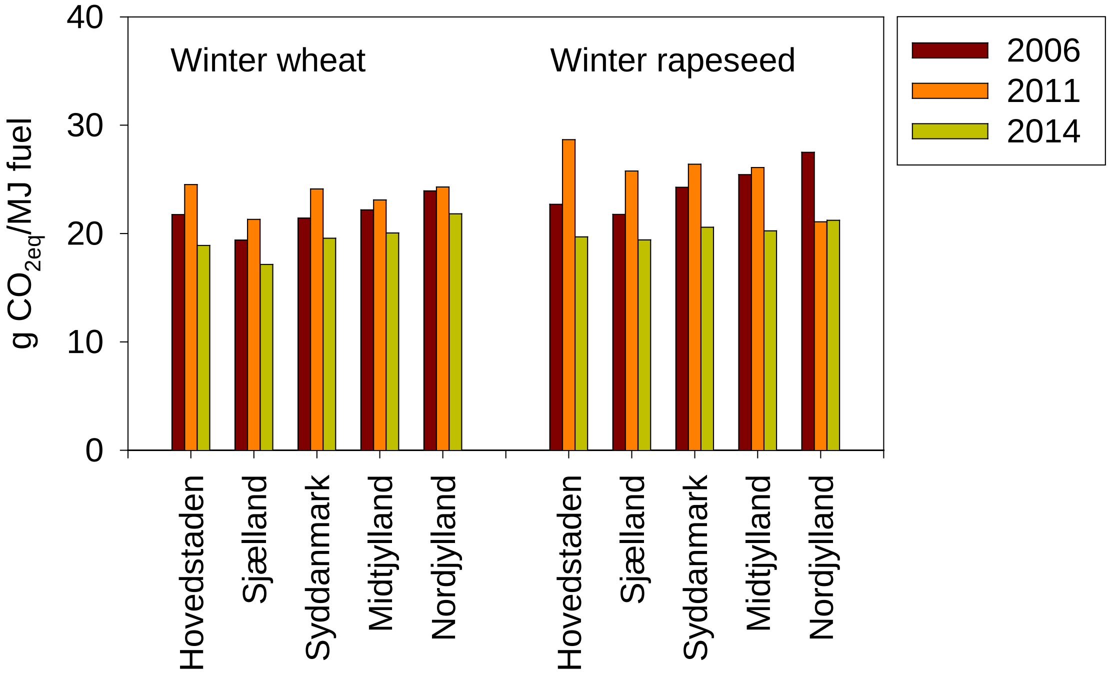

Figure 4. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed calculated according to crop yields in 3 individual years (2006, 2011, 2014).

The effect of yields on the final emission result also reflects the potential effect of cultivation of crop varieties dedicated for biofuel production. Such varieties typically have low protein and high starch content, and give a higher yield relative to the amount of fertilizer N used than other varieties. Ahlgren et al. (2009) showed that under Swedish conditions the use of dedicated wheat varieties for ethanol production reduced the total greenhouse gas emissions by 3 g CO_{2eq}/MJ ethanol.

5.5 Fertilizer production

The production of nitrogen fertilizer represents a substantial contribution to the GHG emissions calculated for the two cropping systems. Therefore, the final result is sensitive to the assumptions made for the environmental load of fertilizer N production. In the present report, a contemporary estimate for the environmental load of fertilizer produced for the Danish market was set to 3.1 kg CO_{2eq}/kg N. This is considerably lower than older estimates of European average values for fertilizer production, which can be found in the literature or in databases. Hence, in the calculations presented by Hvid (2009), a standard value of 8.2 kg CO_{2eq}/kg N was used for the environmental load of fertilizer N production and mainly therefore, a higher total emission for crop cultivation was obtained by Hvid (2009) than in the present base scenario.

To test the effect of the present assumptions made for the environmental load of fertilizer N production, two scenarios were considered. One scenario was that all fertilizers could be supplied with an environmental load of 2.9 kg CO_{2eq}/kg N as suggested by Ahlgreen et al. (2009) and Webb (2010). The other scenario was that 20% of the market share was associated with the worst case European average emission estimate of 6.8 kg CO_{2eq}/kg N; thus resulting in an average emission of 3.8 kg CO_{2eq}/kg N for the Danish market. The changes in the emission results associated with these two scenarios are shown in Fig. 5, which demonstrates a certain importance of the best-available technology (BAT) for reducing N_2O emissions during fertilizer production in Europe. However, more significant advances could come from implementation of new technologies, such as ammonia synthesis using H_2 from gasification of biomass, which supposedly could lower future GHG emissions from fertilizer N production to levels as low as 0.5 kg CO_{2eq}/kg N (Ahlgren et al., 2010).

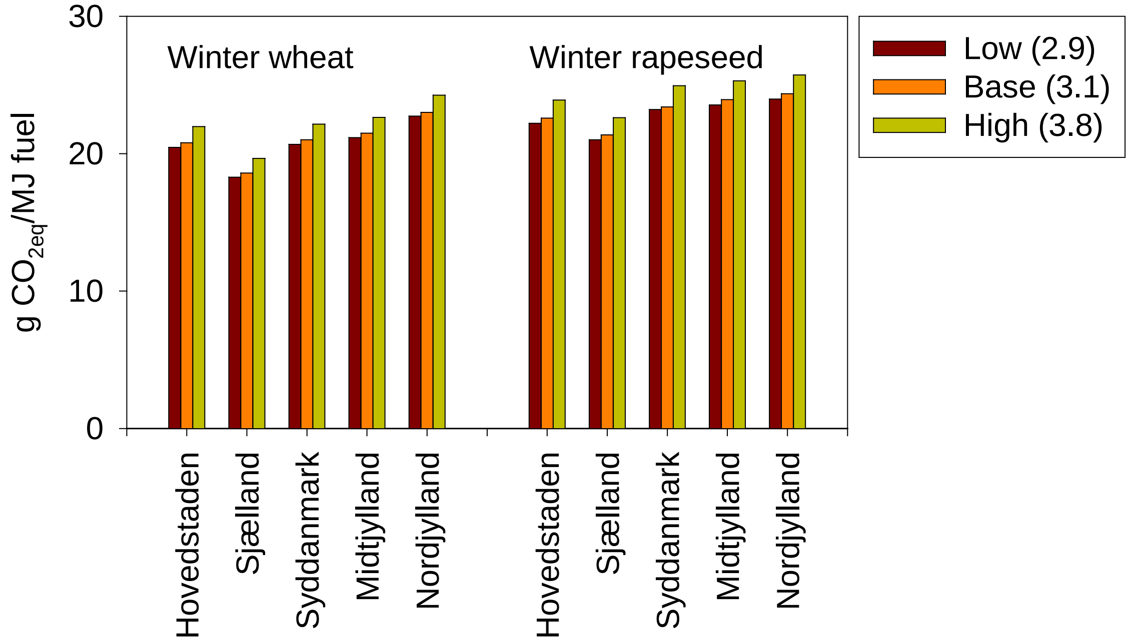

Figure 5. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N assumed to have GHG loads of 2.9 kg CO_{2eq}/kg N (Low), 3.1 kg CO_{2eq}/kg N (base scenario) and 3.8 kg CO_{2eq}/kg N (High).

5.6 Emission of nitrous oxide from soil

The emission of N_2O from application of N-fertilizer to the soil was calculated as the direct and the indirect contributions according to the IPCC (2006) guidelines. This comprises the use of standard emission factors which by the IPCC (2006) are presented as default values with associated uncertainty ranges (Table 17). The relatively large ranges reflect the uncertainty of predicting the N_2O emissions, which are the result of dynamic and heterogeneous microbial soil processes. The emission factors presently suggested by IPCC (2006) have been found to be more appropriate than the emission factors previously proposed

(IPCC, 1997; Mosier et al., 1999). However, Danish national GHG inventories are still required to be estimated by use of the IPCC (1997) emission factors (Table 17).

Table 17. Emission factors (EF) for nitrous oxide emissions including the uncertainty ranges (IPCC, 1997; 2006)

Emission factor (EF)	IPCC (2006)		IPCC (1997)	
	Default value	Uncertainty range	Default value	Uncertainty range
EF for added nitrogen (kg N_2O-N/kg N)	0.01	0.003 - 0.030	0.0125	0.0025 - 0.0225
EF for leached nitrogen (kg N_2O-N/kg N	0.0075	0.0005 - 0.025	0.025	0.002 – 0.12
EF for volatilization and re-deposition (kg N_2O-N/kg NH_3-N)	0.01	0.002 - 0.050	0.01	0.002 – 0.02

Including the uncertainty ranges for the emission factors in the calculations show that the final results can be significantly higher or lower than estimated from the default values (Fig. 6). Thus, the result in all Regions on average varied between 11 and 49 g CO_{2eq}/MJ ethanol for winter wheat and between 13 and 51 g CO_{2eq}/MJ RME for winter rapeseed according to the IPCC (2006) uncertainty range for N_2O emissions from soils (Fig. 6). This illustrates the fundamental demand for better knowledge on N_2O emission factors to calculate more robust estimates for the GHG emissions from cultivation of crops for biofuels.

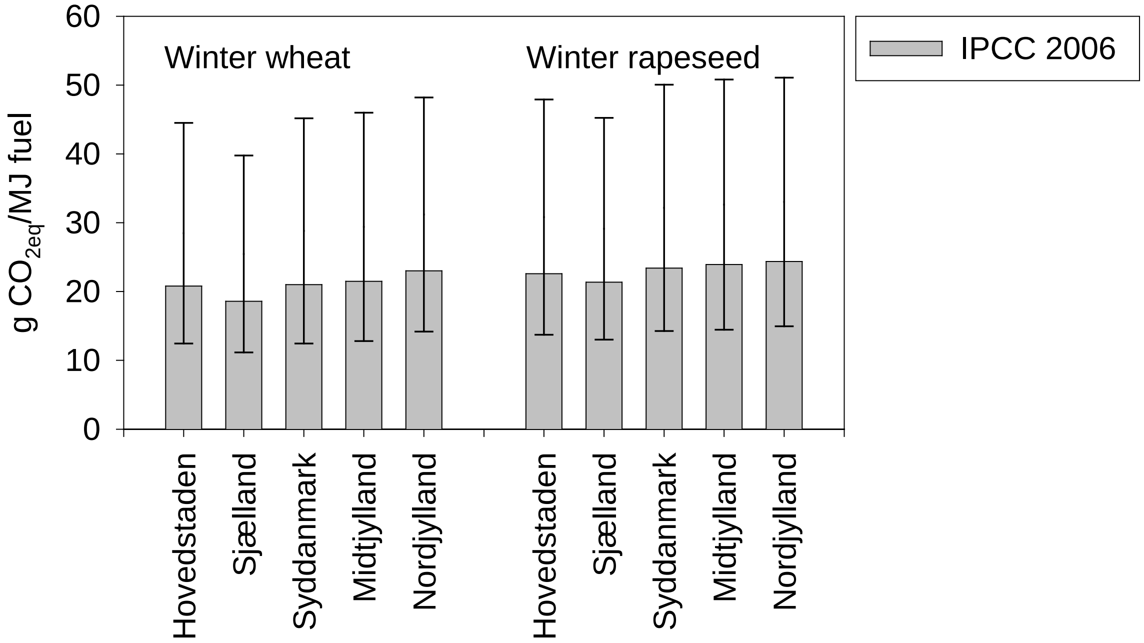

Figure 6. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N according to N_2O emission factors and uncertainty estimates from IPCC (2006). Grey bars show the results for the default emission factors; lines indicate the ranges derived from the uncertainty range for the emission factors.

Evidently, measurements of N_2O emissions are challenging and relatively few studies are available where annual emissions of N_2O have been monitored in cropping systems under Danish conditions. A recent study, however were presented by Chirinda et al. (2010). Here, the annual cumulative N_2O flux and emission factors by N applied in four cropping systems located at Flakkebjerg (Region Sjælland) and Foulum (Region Midtjylland) were presented (Chirinda et al., 2010). Nitrous oxide flux measurements were made in winter wheat field plots of the four rotations. The average organic C content in the Flakkebjerg soil was 9.1 g C/kg dry wt soil, whereas it was considerably higher in the Foulum soil, namely 21.7 g C/kg dry wt soil. At the same time, the average N_2O emission factors for the two soils were estimated to 0.71 ± 0.13 and 0.64 ± 0.08 kg N_2O-N/100 kg N for Flakkebjerg and Foulum, respectively (mean ± standard deviation, n = 4). The values measured under Danish conditions were thus lower that the IPCC (2006) default emission factor for applied N (1 kg N_2O-N/100 kg N) and further the data suggest that increasing C contents may not inevitably lead to higher N_2O emissions, but other factors may influence the N_2O emissions as well.

These data concur with ongoing European studies, where monitoring of GHG emission from rapeseed is prioritized. For example 3-year field trials are conducted on five German research farms to quantify direct N_2O emissions from rapeseed. Results from the first cropping season showed emissions factors lower than predicted by the IPCC (2006) guidelines (Fuss et al., 2014). Likewise in UK, field measurements of N_2O emission factors associated with mineral fertilizers on average were lower than 0.5% (Skiba et al., 2015). No annual emission estimates for rapeseed exists for Denmark to allow the use of an IPCC Tier 2 approach for calculation of GHG emissions. Yet, the sensitivity analysis shown in Fig. 7 indicates the importance of decreased direct emission factors of, e.g., 0.5% as compared to the IPCC (2006) default emission factor of 1.0% for both winter wheat and winter rapeseed.

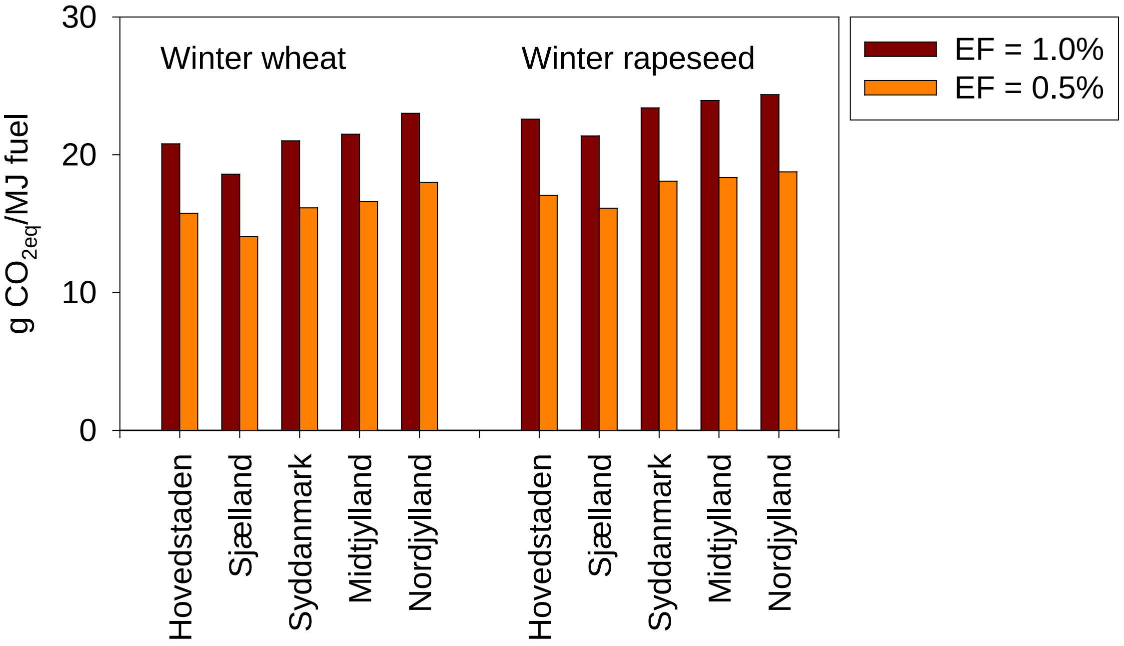

Figure 7. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N according to direct N_2O emission factors (EF) of 1.0% (IPCC, 2006) and an assumed national EF of 0.5%.

5.7 Conclusions from the sensitivity analysis

Sensitivity analyses of the cropping systems showed that the final emission results depended to a large extent on the emission factors assumed for direct N_2O emission from the soil. For example, changes in the emission factor from the IPCC default of 1% to 0.5% decreased the final emission results by ~25% for both winter wheat and winter rapeseed. Better and more precise estimates of N_2O emission factors at the NUTS 2 level therefore would be valuable for more precise estimation of the greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels.

In addition to the soil emission of N_2O, greenhouse gas emissions associated with production of N fertilizer had an impact on the final emission results. Production of mineral fertilizers using best available technology (with catalytic removal of N_2O) has some potential to reduce the emission result for agricultural crops for biofuels but more significant improvements could come from novel technologies. Use of animal slurry as a source of N fertilizer changes the emission result depending on the assumptions made for allocation of the GHG emission from handling and storage of the slurry prior to spreading at the fields. Yet, even with the assumption of zero GHG emission from slurry, the final emission results were similar for mineral and slurry-based fertilizer regimes.

Crop yields determine the amount of biofuel obtained per ha in the agricultural cropping systems. Therefore the final emission results will vary according to the crop yields and the N input required to obtain these yields. Use of dedicated crop varieties for biofuel production thus has a potential to lower the final emission results for biofuel production.

6. ACKNOWLEDGEMENTS

Data on distribution of cropping areas and irrigation on different soil types were provided by Inge T. Kristensen (AU) and data on N leaching in the Danish regions were provided by Christen D. Børgesen (AU). During the work several helpful discussions took place with a number of colleagues including Mogens Nielsen (Yara Denmark), Lars Johansen (DLG), Erik F. Kristensen (AU), Henrik B. Møller (AU), Finn P. Vinther (AU), Jens J. Høy (AgroTech); Søren K. Hvid (DAAS), Torkild Birkmose (DAAS), Jens Søndergaard (Dankalk), Per Ambus (DTU), Steen Gyldenkærne (AU), Mette Hjorth Mikkelsen (AU), Tommy Dalgaard (AU), Thu Lan Thi Nguyen (AU), Kent Gordon (Emmelev A/S), Serina Ahlgren (SLU), Helene Lundkvist (SLU), and Merete Iisager (Statistics Denmark). The report was improved after discussions with Jørgen E. Olesen (AU) and John E. Hermansen (AU). These and other colleagues are thanked for their help.

7. REFERENCES

Ahlgren, S., Bernesson, S., Nordberg, Å., Hansson, P.A., 2010. Nitrogen fertilizer production based on biogas – Energy input, environmental impact and land use. Bioresource Technology, 101, 7181-7184.

Ahlgren, S., Hansson, P.A., Kimming, M., Aronsson, P., Lundkvist, H., 2009. Greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure. Report from Swedish University of Agricultural Sciences (SLU), Dnr SLU ua 12-4067/08, Revised version 2009-09-08, 52 pp.

Ahlgren, S., Hansson, P.A., Kimming, M., Aronsson, P., Lundkvist, H., 2011. Greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure – Implementation of the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Revised edition according to new interpretations of the directive regarding reference land use and crop drying. Swedish University of Agricultural Sciences (SLU), Dnr SLU ua 12-4067/08, 2011-06-22. Available at http://ec.europa.eu/energy/renewables/biofuels/emissions_en.htm (visited November 2012).

Bernesson, S., Nilsson, D., Hansson, P.A., 2004. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. Biomass and Bioenergy 26, 545-559.

Bernesson, S., Nilsson, D., Hansson, P.A., 2006. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. Biomass and Bioenergy 30, 46-57.

Börjesson, P., Tufvesson, L.M., 2011. Agricultural crop-based biofuels - resource efficiency and environmental performance including direct land use changes. Journal of Cleaner Production, 19, 108-120.

Børgesen, C.D., 2009. Landsdækkende modelberegning af kvælstofudvaskning fra landbruget for årene 2003-2007. In C.D. Børgesen, J. Waagepetersen, T.M. Iversen, R. Grant, B. Jacobsen & S. Elmholt (eds.) Mid-term Evaluation of the Action Plan for the Aquatic Environment III. DJF Report Markbrug No. 142. Det Jordbrugsvidenskabelige Fakultet, Aarhus Universitet (in Danish with English summary), pp. 101-111.

Cherubini, F., 2010. GHG balances of bioenergy systems – overview of key steps in the production chain and methodological concerns. Renewable Energy 35, 1565–1573.

Chirinda, N., Carter, M.S., Albert, K.R., Ambus, P., Olesen, J.E., Porter, J.R., Petersen, S.O., 2010. Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. Agriculture, Ecosystems and Environment 136, 199–208.

DAAS, 2008a (Danish Agricultural Advisory Service). Vinterhvede – dyrkningsvejleding. http://app4.landscentret.dk/DyrkVejl/Forms/Main.aspx?page=Vejledning&cropID=12 (visited April 2010).

DAAS, 2008b (Danish Agricultural Advisory Service). Vinterraps – dyrkningsvejleding. http://app4.landscentret.dk/DyrkVejl/Forms/Main.aspx?page=Vejledning&cropID=13 (visited April 2010).

DAAS, 2009a (Danish Agricultural Advisory Service). Budgetkalkuler 2009-2010. www.landbrugsinfo.dk/Diverse/KA/Filer/Budgetkalkuler_2010_salg.pdf (visited April 2010).

DAAS, 2009b (Danish Agricultural Advisory Service). Datablad – klimapåvirkning ved dyrkning af vinterhvede. www.landbrugsinfo.dk/Planteavl/Afgroeder/Korn/Vinterhvede/Filer/pl_09_033_datablad.pdf (visited May 2010).

Dalgaard, T., Halberg, N., Jørgensen, M.H., 2004. Status for energiinput og –output i økologisk jordbrug samt muligheder for energibesparelser. In: Jørgensen, U., Dalgaard, T. (eds.) Energi i økologisk jordbrug – reduktion af fossilt energiforbrug og produktion af vedvarende energi, pp. 25-45. Forskningscenter for Økologisk Jordbrug.

Dalgaard, T., Dalgaard, R., 2006. Model til beregning af fossilt energiforbrug i jordbrugssystemer med og uden mekanisk ukrudtsbekæmpelse. In: Odderskær, P., Topping, C., Petersen, M.B., Rasmussen, J., Dalgaard, T., Erlandsen, M. (2006) Ukrudtsstriglingens effekter på dyr, planter og ressourceforbrug, bilag D, pp. 115-127. Miljøministeriet, Bekæmpelsesmiddelforskning fra Miljøstyrelsen, Nr. 105.

Elsgaard L, Olesen JE, Hermansen JE, Børgesen CD, Kristensen, IT, 2013. Regional greenhouse gas emissions from cultivation of winter wheat and winter rapeseed for biofuels in Denmark. Acta Agriculturae Scandinavica, Section B, 63, 219-230.

Energinet.dk, 2015. Miljødeklarationer for el. www.energinet.dk (visited May 2015).

European Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF (visited April-May 2010).

Fossum, J-P, 2014. Calculation of Carbon Footprint of Fertilizer Production. Note issued by Yara HESQ/ Jan-Petter Fossum. http://www.yara.com/doc/122597_2013_Carbon_footprint-of_AN_Method_of_calculation.pdf. (visited May 2015).

Fuss, R., Andres, M., Hegewald, H., Kesenheimer, K., Köbke, S., Räbiger, T., Suarez, T., Stichnothe, H., Flessa, H., 2014. Direct nitrous oxide emissions from rapeseed in Germany Geophysical Research Abstracts, Vol. 16, EGU 2014-14005, EGU General Assembly.

Granli, T., Bøckman, O.C., 1994. Nitous oxide from agriculture. Norwegial Journal of Agricultural Sciences, Supplement No. 12, 7-128.

Greve MH, Christensen OF, Greve MB, Bou-Kheir R (2014) Change in peat coverage in Danish cultivated soils during the past 35 years. Soil Science, 179, 250-257.

Greve MH, Greve MB, Christensen OF, Bou-Kheir R (2012) Mapping of the organogenic soils on agricultural land. Final report, SINKS (DP6), Aarhus University.

Hvid, S.K., 2009. Klimapåvirkning ved dyrkning – vinterhvede som eksempel. Datasheet from Danish Agricultural Advisory Service. www.landbrugsinfo.dk/Planteavl/Afgroeder/Korn/Vinterhvede/Sider/pl_09_033.aspx (visited May 2015).

IPCC, 1997. Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories. Chap. 4. Agriculture: nitrous oxide from agricultural soils and manure management.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventory. Volume 4 Agriculture, Forestry and Other Land Use.

Jenssen, T.K., 2010. Beregning af gødningsproduktionens carbon footprint. Note from YARA Health, Environment, Safety & Quality. www.yara.dk/doc/302912010_Carbon_Footprint_of_AN_Calculation_Method_final.pdf. (visited May 2010)

Jenssen, T.K., Kongshaug, G., 2003. Energy Consumption and Greenhouse Gas Emissions in Fertiliser Production. The International Fertiliser Society, York, UK, Proceedings No. 509.

Kristensen, K., Waagepetersen, J., Børgesen, C.D., Vinther, F.P., Grant, R., Blicher-Mathiesen, G., 2008. Reestimation and further development in the model N-LES, N-LES3 to N-LES4. DJF Plant Science 139. Faculty of Agricultural Science, Aarhus University, 25 pp.

LowCVP, 2004. Well-to-Wheel Evaluation for Production of Ethanol from Wheat. A Report by the LowCVP Fuels Working Group, WTW Sub-Group. FWG-P-04-024.

Mikkelsen, M.H., Gyldenkærne, S., Poulsen, H.D. Olesen, J.E., Sommer, S.G., 2006. Emission of ammonia, nitrous oxide and methane from Danish Agriculture 1985-2002. Methodology and Estimates, 90 pp. National Environmental Research Institute, Ministry of the Environment, Denmark. http://www2.dmu.dk/Pub/AR231.pdf (visited May 2010).

Ministry of Food, Agriculture and Fisheries, 2015. Vejledning om Gødsknings- og Harmoniregler.

Mogensen, V.O, Jensen, C.R., 2002. Markafgrøder, klima og vandforsyning.DSR-forlag, Den Kgl. Veterinær- og Landbohøjskole.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput O., 1999. An overview of the revised 1996 IPCC guidelines for national greenhouse gas inventory methodology for nitrous oxide from agriculture. Environmental Science & Policy 2: 325-333.

Nielsen, O.K., Lyck, E., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Albrektsen, R., Hjelgaard, K., Johannsen, V.K., Vesterdal, L., Rasmussen, E., Arfaoui, K., Baunbæk, L., 2013. Denmark's National Inventory Report 2013. Emission Inventories 1990-2011 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE – Danish Centre for Environment and Energy, 1202 pp. Scientific Report from DCE – Danish Centre for Environment and Energy.

Nielsen, P.H., Nielsen, A.M., Weidema, B.P., Dalgaard, R., Halberg, N., 2003. LCA Food Data Base. www.lcafood.dk.

Olesen, J.E., Weiske, A., Asman, W.A., Weisbjerg, M.R., Djurhuus, J., Schelde, K., 2004. FarmGHG. A model for estimating greenhouse gas emissions fromlivestock farms. Documentation. Danish Institute of Agricultural Sciences.

Petersen, J., Haastrup, M., Knudsen, L., Olesen, J.E., 2010. Causes of yield stagnation in winter wheat in Denmark. DJF Report Plant Science No. 147. Tjele, Denmark: Faculty of Agricultural Sciences, Aarhus University.

Petersen, J., Sørensen, P., 2008. Gødningsvirkning af kvælstof i husdyrgødning – Grundlag for fastlæggelse af substitutionskrav. DJF markbrug nr. 138, Det Jordbrugsvidenskabelige Fakultet, Aarhus Universitet.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agricultural Systems 57, 599-630.

Sahrawat, K.L., Keeney, D.R., 1986. Nitrous oxide emission from soils. Advances in Soil Sciences 4, 103–148.

SEGES, 2015. Resultat af kalkstatistikken for 2015.

Skiba, U., McNamara, N., Thorman, R.E., Rees, B., 2015. Overview of N_2O emissions from oilseed rape in the UK. Presentation at the international workshop: “Greenhouse Gas Emission from Oilseed Rape Cropping and Mitigation Options”, 4-5 March, 2015, Braunschweig, Germany. Available at: https://www.ti.bund.de/en/ak/news-and-service/reviews-of-conferences-and-workshops/international-workshop-greenhouse-gas-emission-from-oilseed-rape-cropping-and-mitigation-options/. (visited May 2015).

Statistics Denmark, 2015a. HST77: Harvest by Region, Crop and Unit. www.statistikbanken.dk. (visited May 2015).

Statistics Denmark 2015b. PEST1: Salget af pesticider til anvendelse i landbrugets planteavl samt behandlingshyppighed efter pesticidgruppe og måleenhed. www.statistikbanken.dk. (visited May 2015).

Statistics Denmark, 2015c. HALM1: Straw yield and use by region, crop, unit and use. www.statistikbanken.dk. (visited May 2015).

Swedish Environmental Protection Agency, 2007. Sweden's National Inventory Report 2008. Submitted under the United Nations Framework Convention on Climate Change. www.naturvardsverket.se/upload/02_tillstandet_i_miljon/utsl%C3%A4ppsdata/vaxthusgaser/2007/nir_klimatrapportering_2008.pdf (visited May 2010).

Vinther, F.P., Hansen, S., 2004. SimDen – en simple model til kvantificering af N_2O emission og denitrifikation. DJF Rapport, Markbrug nr. 104. Danmarks JordbrugsForskning.

Webb, J., O'Brien, S., Vad, K., Cardenas, L., Misselbrook, T.H., Garstang, J., 2010. Regional emissions from biofuels cultivation. Revised report: December 2010. Final Report to the Department for Transport. AEA Technology plc, UK.

Wood, S., Cowie, A., 2004. A review of greenhouse gas emission factors for fertiliser production, IEA bioenergy task 38. www.ieabioenergy-task38.org/publications/GHG_Emission_Fertilizer%20Production_July2004.pdf (visited May 2010).

Yara, 2010. Yara indfører carbon footprint garanti. Press release, Yara Denmark, May 2010. www.yara.dk/doc/30303Pressemedelelse%20Final.pdf (visited May 2010).

8. **APPENDIX -** EU Pilot, File ref n°: 1322/10/ENER

(overleaf)

European Commission

EU Pilot

12/08/2010

File ref n°:	1322/10/ENER
Member State:	DK
Commission service:	ENER
Issue area:	Energy/Electricity produced from renewable energy sources
File nature:	Own Initiative / Commission

Contact person Commission service:	Ms SCHNEIDER Anne
Contact person Member State:	Mr LUND Lars Bo Kirketerp

File history

- **04/08/2010:** Draft file created by Energy / SCHNEIDER Anne
- **10/08/2010:** File submitted to Member State in EU PILOT database - Energy / SCHNEIDER Anne
- **12/08/2010:** File accepted by Member State - Denmark / Mr LUND Lars Bo Kirketerp (*Number of days between introduction and acceptance by Member State:* ***2***)

File status

- **File status:** File open

Title:

- Submission to the Commission of the report required by Article 19 (2) of Directive 2009/28/EC on the promotion of the use of energy from renewable sources (1)

Issue Description:

- **Commission service language:** We are writing to you with respect to the report you submitted under Article 19(2) of Directive 2009/28/EC (1) for which we would like to thank you. However, we have now reviewed the report and it appears that some further elements are needed to comply with the requirements set out in the Directive. The following point need further clarifications:

  • The report introduces a reference case which is not according to IPCC Tier1 methodology, where the "background" emissions are already deducted (see footnote 7 of chapter 11 of the IPCC guidelines for National GHG inventories). The revision of the report shall exclude the subtraction of a reference when IPCC Tier1 methodology is applied.

  The Commission is of the view that the quality of the report could be further improved if the following points were taken into account:
  • The calculations include crop drying, which shall be excluded in the "cultivation step".
  • The high SOC content in cropland in Nordjylland is likely to influence the N2O emissions from that region. Please provide a discussion on the extent that the high SOC content influences emissions

from cultivation.
- The inclusion of GHG emissions values for biogas from manure is not necessary, as this is considered waste, and thus bears no emissions from the point of collection.

In the light of the above, we would be grateful if you could ask the competent authorities to respond to the above mentioned points at your earliest convenience and not later than 6 weeks of receipt of this letter.

Once this time-limit has expired and if the Commission considers that your Government has failed to fully fulfil its obligations under Article 19(2) of the Directive 2009/28/EC, it may issue a Letter a Formal Notice pursuant to Article 258 TFUE. The Commission may also ask for additional information to be submitted in relation to this report.

(1) OJ L140/16, 5.6.2009