

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

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PREFACE

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 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.”

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.

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). LCA methodology and interpretations of the EU Directive 2009/28/EC were generally used according to the report of Ahlgren et al. (2009) 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, 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	23.0	24.9
Sjælland	20.1	23.7
Syddanmark	23.3	26.8
Midtjylland	23.6	27.4
Nordjylland	24.2	28.2

Sensitivity analyses of the cropping systems showed that the final emission results depended to a large extent on the emission factors assumed for N₂O emission from the soil. Thus, the uncertainty range reported for the IPCC N₂O emission factors (IPCC, 2006) caused the final emission results in all Regions (on average) to vary between 14 and 47 g CO_{2eq}/MJ ethanol for winter wheat and between 17 and 53 g CO_{2eq}/MJ RME for winter rapeseed.

Likewise, the assumptions made for GHG emissions associated with production of N fertilizer had a major impact on the final emission results. Thus, production of mineral fertilizers using best available technology (with catalytic removal of N₂O) has the potential to reduce the emission result as compared to N production at older European facilities.

The emissions calculated for the present base scenarios were generally equal to or lower than the emissions stated as disaggregated default values for cultivation in the Directive 2009/28/EC. Only the emission result for ethanol from winter wheat in Region Syddanmark, Midtjylland and Nordjylland were slightly higher (1 to 5%) than the default values.

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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^o: 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 these 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_{cc}), 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), 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 on 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_{cc} :

- Emissions from the extraction or cultivation of raw materials, e_{cc} , 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. 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.

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_{cc} . 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 N₂O 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 N₂O 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 N₂O 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 2009 was obtained from Energinet.dk (2010). These data were considered to be representative also for 2010. So far, the electricity systems in Eastern and Western Denmark are separated and therefore separate environmental declarations are reported by Energinet.dk. According to Energinet.dk (2010) 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 489 g CO_{2eq}/kWh was then used for electricity in Eastern Denmark, and a value of 461 g CO_{2eq}/kWh was used for Western 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 2006-2009. 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 2010 situation (i.e., the first year in which the EU directive 2009/28/EC could possibly come into effect) 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.



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 from Statistics Denmark (2010a)

Region	Winter wheat (hkg/ha)					Winter rapeseed (hkg/ha)				
	2006	2007	2008	2009	mean	2006	2007	2008	2009	mean
Hovedstaden	31.5	28.1	25.8	29.4	28.7	6.7	8.4	6.9	6.7	7.6
Sjælland	155.7	154.3	136.3	155.1	150.4	25.7	40.3	29.7	25.7	32.5
Syddanmark	184.8	187.8	175.7	207.7	189.0	35.1	55.0	48.5	35.1	46.3
Midtjylland	176.7	183.2	167.9	195.1	180.7	33.7	46.7	53.9	33.7	45.1
Nordjylland	128.4	127.4	122.8	141.9	130.1	22.1	27.8	32.6	22.1	27.4

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 from Statistics Denmark (2010a)

Region	Winter wheat (hkg/ha)					Winter rapeseed (hkg/ha)				
	2006	2007	2008	2009	mean	2006	2007	2008	2009	mean
Hovedstaden	68.3	65.6	77.1	75.4	71.6	36.9	32.8	40.1	38.1	37.0
Sjælland	77.0	71.6	88.7	89.3	81.7	38.7	34.5	40.1	43.5	39.2
Syddanmark	71.3	63.8	79.2	80.1	73.6	35.7	32.8	36.8	38.1	35.9
Midtjylland	68.5	65.1	75.6	79.4	72.2	33.6	32.4	35.1	38.2	34.8
Nordjylland	64.4	63.0	74.0	75.9	69.3	30.8	31.5	34.5	37.1	33.5

3.2 Seed rate

Under Danish conditions winter wheat is preferably established in mid-September at a plant density of 290 plants per m² 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.

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,

2009). Guiding standards for phosphorous (P) and potassium (K) were likewise included in the calculations according to the Ministry of Food, Agriculture and Fisheries (2009):

- winter wheat: 22 kg P/ha and 66 kg K/ha
- winter rapeseed: 30 kg P/ha and 89 kg K/ha

Table 3. Danish nitrogen standards (kg N/ha) for 2009/2010 (Ministry of Food, Agriculture and Fisheries, 2009)

Crop	Nitrogen standards for different soil types (kg N/ha)				
			Irrigated		
	Coarse sand JB 1+3	Fine sand JB 2+4 & 10-12 ^a	sandy soil JB 1-4	Sandy loam JB 5-6	Loamy soils JB 7-9
Winter wheat	146	149	166	161	174
Winter rapeseed	166	177	177	183	186

^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 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 and Environment, 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 2010, the data were recalculated to represent the 2010 situation (Table 4 and 5).

Table 4. Area estimates (ha) of soil types cropped with winter wheat in 2010 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	69	0	551	41	20164	13496	22917	13865	7138	2778
JB 2	204	36	1367	137	1202	345	7539	3713	40243	15903
JB 3-4	7256	829	19843	2675	48592	18492	74863	22654	48665	15254
JB 5-6	13651	948	88835	8548	96532	15479	57082	9250	16296	3408
JB 7	6778	165	35287	2563	14578	2543	8727	1088	5977	1424
JB 8-10	164	0	852	58	3109	1128	1800	562	1316	225
JB 11	536	108	2798	818	4741	2723	6455	3289	9811	4861
JB 12	40	9	818	199	82	30	1342	594	679	168
SUM	28699	2095	150350	15040	189000	54236	180725	55015	130125	44020

Table 5. Area estimates (ha) of soil types cropped with winter rapeseed in 2010 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	45	3	76	16	6966	4408	7638	4249	2421	909
JB 2	65	13	279	55	390	132	2370	1070	10465	4168
JB 3-4	3661	463	5933	895	13288	4795	21166	5967	10570	3309
JB 5-6	2725	285	20206	2025	21260	3432	11620	1834	2248	521
JB 7	959	53	5134	522	2713	336	1370	199	551	82
JB 8-10	9	0	158	0	525	198	103	13	65	24
JB 11	158	46	700	196	1099	646	787	438	964	552
JB 12	4	1	14	1	9	5	20	8	116	54
SUM	7626	864	32500	3709	46250	13952	45074	13778	27400	9618

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 (147.5 kg N/ha for winter wheat and 171.5 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	161	178
Sjælland	162	181
Syddanmark	160	179
Midtjylland	157	176
Nordjylland	156	175

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 N₂O, 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 by Ahlgren et al. (2009) to represent a present ‘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 is considered to be a realistic emission factor to be used in the present calculations as this is reported as the average carbon footprint for Yara fertilizers supplied to Denmark (Jenssen, 2010).

For the rest of the Danish market (ca. 40% of the market share) different European producers from, e.g., Balticum, Poland, Russia, Netherlands and Germany are involved. For this market share, the average European emission factor estimate of 6.8 kg CO_{2eq}/kg N (Jenssen and Kongshaug, 2003) may represent a worst case scenario. However, to avoid a worst case scenario in the baseline calculations it was assumed that since the time of the review by Jenssen and Kongshaug (2003) an average improvement of 20% in relation to the greenhouse gas emissions has been obtained among European producers. This estimate was based on discussions with specialists in the Danish fertilizer business.

Based on the market shares and carbon footprints, a contemporary estimate of greenhouse gas emissions associated with production of commercial fertilizers (E_{fert}) for the Danish market in 2010 would be 4.3 kg CO_{2eq}/kg N:

$$E_{fert} = 3.52 \text{ kg CO}_{2eq}/\text{kg N} \times 60\% + 0.8 \times 6.8 \text{ kg CO}_{2eq}/\text{kg N} \times 40\% = 4.3 \text{ kg CO}_{2eq}/\text{kg N}$$

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% 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 (2010b) the average amount of active substance applied per treatment was 0.56 kg/ha in 2008. 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 ₂ O	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 ‘budget kalkuler 2009-2010’ 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 lubrication oil consumed was rated to 0.7% of the diesel consumed and the emission associated with production of lubrication 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 nr. 7) and by 0.9 for calculations on sandy soils (here JB nr. 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 (DAAS, 2010) as shown in Table 9. Thus, data on the mean lime use during 2000-2009 was combined with data on the cultivated area to provide an estimate of the area-specific use of agricultural lime (183 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 2000-2009 (DAAS, 2010)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Mean
Total lime use (1000 t CaCO ₃)	614	479	557	537	382	497	438	434	518	410	487

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 2.12 kg CO_{2eq}/mm/ha as calculated for electricity supplied in Western Demark and 2.25 kg CO_{2eq}/mm/ha as calculated for electricity supplied in Eastern Denmark.

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 N₂O increases with increasing N availability, but other major controllers of the N₂O 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 N₂O is highly variable in time and space and it is challenging, therefore, to model and predict the N₂O 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 N₂O produced from added N in the soil system and an indirect contribution of N₂O produced from N that escapes the cropping system via leaching and volatilization.

Direct N₂O emission in the IPCC (2006) methodology is calculated from the empirical assumption that 1% of the added nitrogen in soil system is emitted as N₂O. 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:

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

F_{SN} = Amount of synthetic fertilizer applied (kg N/ha)

F_{ON} = Amount of annual manure applied (kg N/ha)

F_{CR} = Amount of N crop residues above ground and below-ground (kg N/ha)

EF_N = IPCC emission factor for added nitrogen (0.01 kg N₂O-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 2006-2008 (Statistics Denmark, 2010c). 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.

Table 10. Percentage of cropped area with non-salvaged straw (%). Calculated from data in Statistics Denmark (2010c)

Region	Winter wheat				Winter rapeseed			
	2006	2007	2008	Mean	2006	2007	2008	Mean
Hovedstaden	57	57	48	55	97	92	93	94
Sjælland	32	33	24	30	87	88	72	83
Syddanmark	44	40	25	36	88	87	63	79
Midtjylland	49	41	27	39	84	86	70	79
Nordjylland	55	45	37	46	90	87	75	83

Table 11. Parameters included to calculate the direct N₂O emission from crop residues. Data from Statistics Denmark (2010c) 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 (Christen D. Børgesen, personal communication). No deductions were made for leaching of nitrogen deposited via air pollution. To calculate the contribution of N₂O from the amount of leached N, the IPCC (2006) emission factor of 0.0075 kg N₂O-N/kg N was applied.

Table 12. Estimated average leaching losses (kg N/ha/year) from winter wheat and winter rapeseed. 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 N₂O from the amount of volatilized NH₃ the IPCC (2006) emission factor of 0.01 kg N₂O-N/kg NH₃-N was applied.

In summary, indirect nitrous oxide emissions (kg N₂O/ha) were calculated as:

$$N_2O \text{ (indirect)} = (F_L \times EF_L + F_A \times EF_D) \times 44/28, \quad \text{where:}$$

F_L = Amount of nitrogen lost through leaching (kg N/ha)

EF_L = IPCC emission factor for leaked nitrogen (0.0075 kg N₂O-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 N₂O-N/kg NH₃-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 CO₂ 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:

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

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 to 16). The total emission estimates ranged from 20.1 to 24.2 g CO_{2eq}/MJ ethanol for winter wheat (Table 14) and from 23.7 to 28.2 g CO_{2eq}/MJ RME for winter rapeseed (Table 16). The calculations showed that the two major contributors to the final result were the GHG emissions associated with fertilizer production and direct emissions of N₂O. These two emissions accounted for 73 to 79% of the total emissions. Differences in the GHG emissions in the five Regions were less than 99 g CO_{2eq}/ha (< 5%) for both cropping systems with the highest emissions estimated for 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 ₂ O emission from soil	Indirect N ₂ O emission	Total (kg CO _{2eq} /ha)
Hovedstaden	184	8	84	760	9	870	191	2106
Sjælland	185	8	84	765	9	858	184	2093
Syddanmark	181	36	84	756	9	851	275	2192
Midtjylland	179	42	84	743	9	839	278	2174
Nordjylland	178	49	84	738	9	838	253	2149

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 ₂ O emission from soil	Indirect N ₂ O emission	Total (g CO _{2eq} /MJ ethanol)
Hovedstaden	2.0	0.1	0.9	8.3	0.1	9.5	2.1	23.0
Sjælland	1.8	0.1	0.8	7.3	0.1	8.2	1.8	20.1
Syddanmark	1.9	0.4	0.9	8.0	0.1	9.1	2.9	23.3
Midtjylland	1.9	0.5	0.9	8.1	0.1	9.1	3.0	23.6
Nordjylland	2.0	0.5	0.9	8.3	0.1	9.5	2.9	24.2

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 17% for winter wheat and 16% 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 generally equal 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). Only the results for winter wheat in regions Syddanmark, Midtjylland and Nordjylland were slightly higher (1 to 5%) than 23 g CO_{2eq}/MJ ethanol.

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 ₂ O emission from soil	Indirect N ₂ O emission	Total (kg CO _{2eq} /ha)
Hovedstaden	203	22	84	854	9	990	172	2334
Sjælland	208	16	84	867	9	995	165	2344
Syddanmark	203	62	84	858	9	968	249	2433
Midtjylland	199	71	84	845	9	951	248	2407
Nordjylland	197	85	84	841	9	948	231	2395

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 ₂ O emission from soil	Indirect N ₂ O emission	Total (g CO _{2eq} /MJ RME)
Hovedstaden	2.2	0.2	0.9	9.1	0.1	10.6	1.8	24.9
Sjælland	2.1	0.2	0.8	8.8	0.1	10.0	1.7	23.7
Syddanmark	2.2	0.7	0.9	9.5	0.1	10.7	2.7	26.8
Midtjylland	2.3	0.8	1.0	9.6	0.1	10.8	2.8	27.4
Nordjylland	2.3	1.0	1.0	9.9	0.1	11.2	2.7	28.2

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 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 separate 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 to 93 L/ha depending on the soil type. Using diesel consumption estimates calculated according to Dalgaard and Dalgaard (2006) would increase the final emission results in Table 14 and 16 by ca. 5%.

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. 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 CH₄ and N₂O 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. (2009) 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 N₂O and CH₄ 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 N₂O and 47.1 gG CH₄ (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 supplied to the cropping systems in the form of mineral fertilizer (*cf.* Table 6). Direct and indirect N₂O emission from applied slurry N was calculated according to IPCC (2006). For the estimates of indirect N₂O emission, the default fraction (20%) of applied organic N fertilizer that volatilises as NH₃ 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).

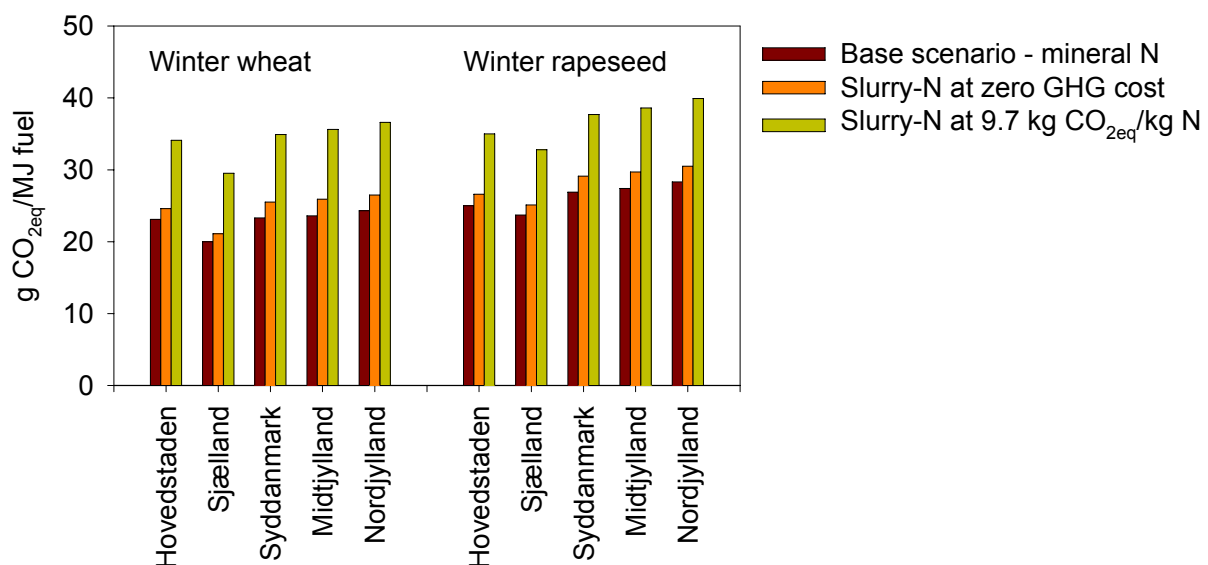


Figure 2. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed in a base scenario with mineral N fertilization and in scenarios with combined slurry (25 t/ha) and mineral N fertilization. Calculations assumed that production of slurry N was associated with 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 45.4 kg CO_{2eq}/hkg grain for Region Midtjylland, which has a 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 relatively limited impact on the final emission results. Changes in irrigation had the highest effect in Region Nordjylland, which has the highest proportion of irrigated crops.

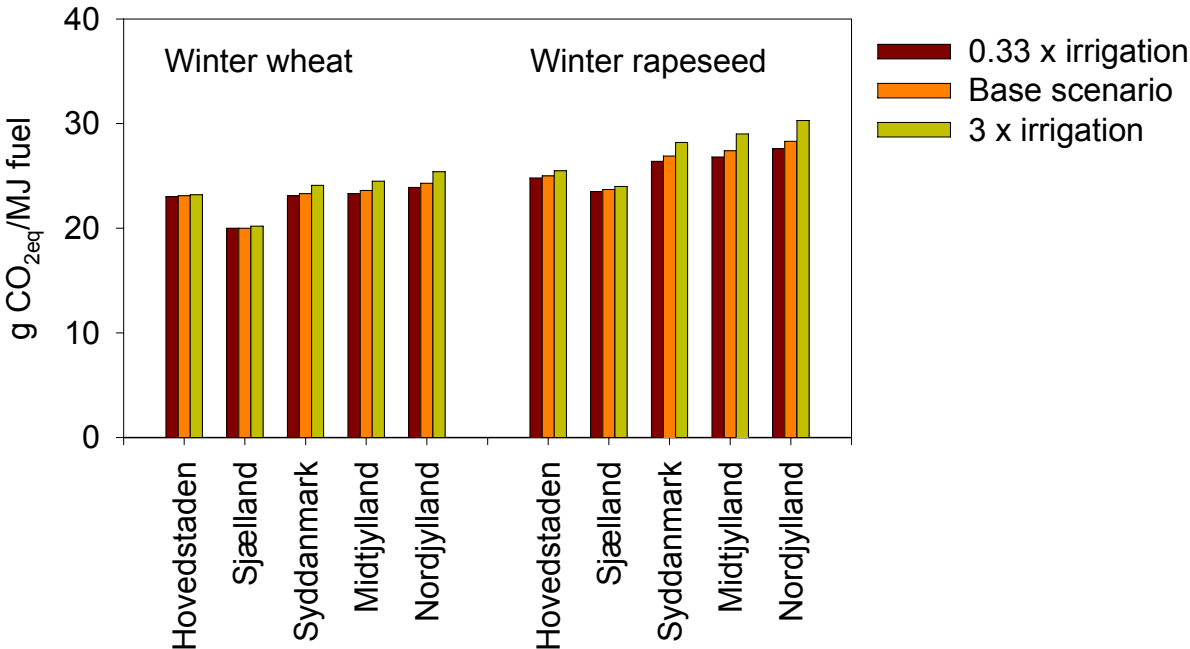


Figure 3. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed assuming different needs for irrigation corresponding to one third and three times the value used in the present base scenario calculations.

5.4 Crop yields

Data on crop yields from Statistics Denmark were reported on the NUTS 2 level from the years 2006-2009. 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 (2007 to 2009) are shown in Fig. 4, which demonstrates the importance of the yield estimates.

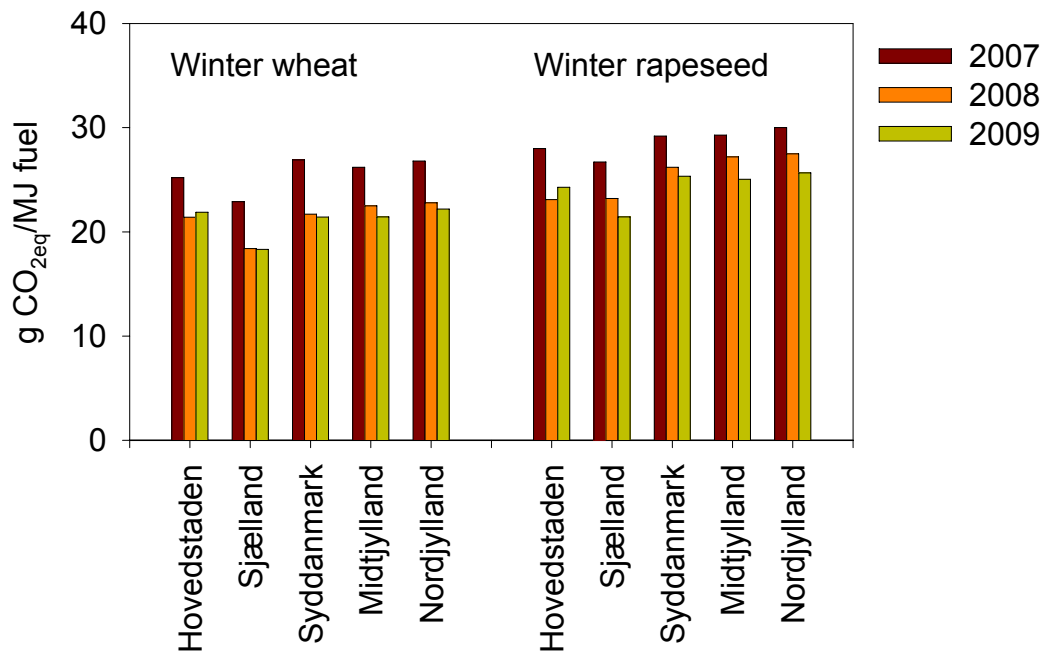


Figure 4. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed calculated according to crop yields in three individual years (2007-2009).

To qualify the yield estimates for 2010, Region Syddanmark was taken as an example and data for 1990 to 2006 (Statistics Denmark, 2010d) were recalculated from the older Counties to the new Region (Fyns Amt, Sønderjyllands Amt and Ribe Amt were merged to become Region Syddanmark). This calculation showed a good agreement between the yield estimates based on 4 years of data from the Region (2006-2009) and the yield estimates based on 19 years of data from the Counties and Regions (Fig. 5).

The effect of yields on the final emission result also reflects the potential effect of cultivation of wheat varieties dedicated for bioethanol 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 wheat 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.

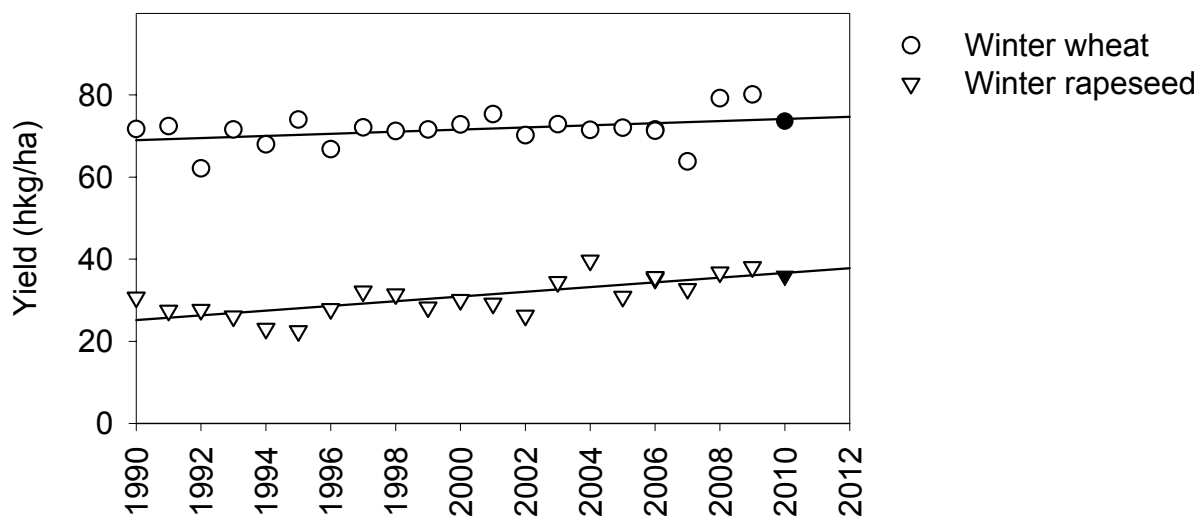


Figure 5. Yields of winter wheat (open circles) and winter rapeseed (open triangles) for Region Syddanmark as re-calculated from County data (1990-2006) and as available for the Region (2006-2009). Lines represent linear regression for predicting the yield in 2010 from the 1990-2009 data. Closed symbols represent the yield estimates for 2010 used in the base scenario that were based on the data available for the Region in 2006-2009.

5.5 Fertilizer production

The production of nitrogen fertilizer represents a major 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 derived which amounted to 4.3 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 the environmental load of less than 4 kg CO_{2eq}/kg N as guaranteed by Yara (2010). The other scenario was that the European average emission estimate of 6.8 kg CO_{2eq}/kg N applied for all fertilizer N supplied (considered by Ahlgren et al. (2009) to represent a present 'worst case' scenario). The changes in the emission results associated with these two scenarios are shown in Fig. 6, which demonstrates the importance of the technological improvements for reducing N₂O emissions during fertilizer production in Europe.

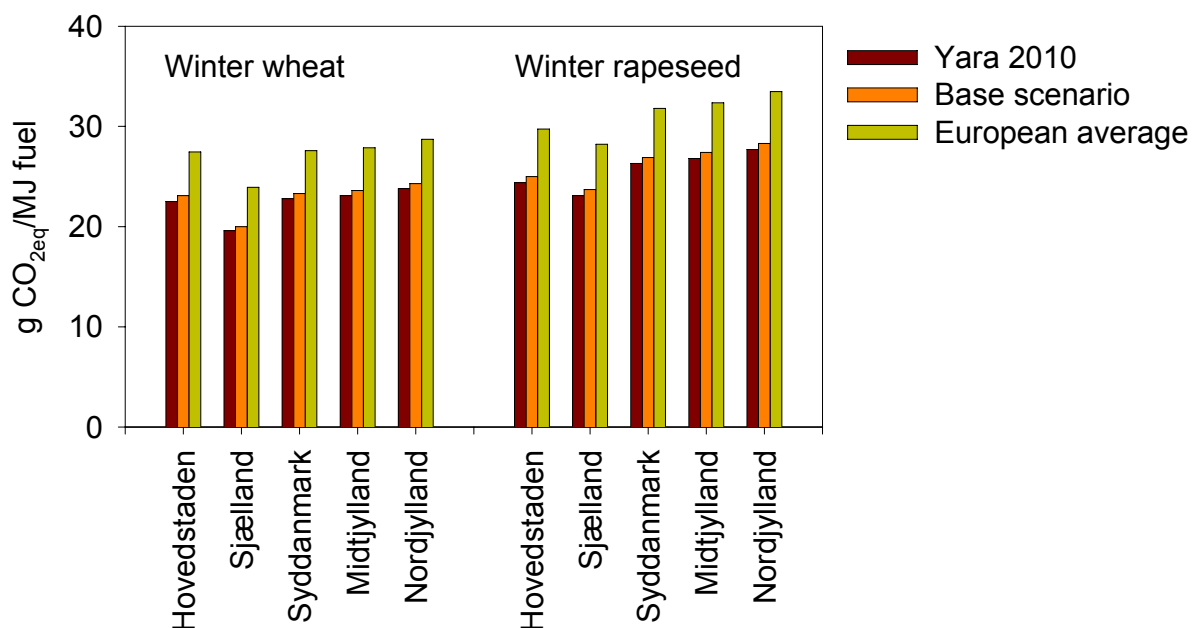


Figure 6. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N assumed to have GHG loads of 4 kg CO_{2eq}/kg N (Yara 2010), 4.3 kg CO_{2eq}/kg N (base scenario) and 6.8 kg CO_{2eq}/kg N (European average).

5.6 Emission of nitrous oxide from soil

The emission of N₂O 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 N₂O 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 ₂ O-N/kg N)	0.01	0.003 - 0.030	0.0125	0.0025 - 0.0225
EF for leaked nitrogen (kg N ₂ O-N/kg N)	0.0075	0.0005 - 0.025	0.025	0.002 - 0.12
EF for volatilization and re-deposition (kg N ₂ O-N/kg NH ₃ -N)	0.01	0.002 - 0.050	0.01	0.002 - 0.02

The effects of calculation of N₂O emission according to the IPCC (1997) and the IPCC (2006) emission factors are shown in Fig. 7. The final emission results are on average decreased by 24% when calculated according to the emission factors from 2006. 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. 8). Thus, the result in all Regions on average varies between 14 and 47 g CO_{2eq}/MJ ethanol for winter wheat and between 17 and 53 g CO_{2eq}/MJ RME for winter rapeseed according to the IPCC (2006) uncertainty range for N₂O emissions from soils (Fig. 8). This illustrates the demand for better knowledge on N₂O emission factors to calculate more robust estimates for the GHG emissions from cultivation of crops for biofuels.

Evidently, measurements of N₂O emissions are challenging and relatively few studies are available where annual emissions of N₂O have been monitored in cropping systems under Danish conditions. A recent study, however were presented by Chirinda et al. (2010). Here, the annual cumulative N₂O 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 N₂O emission factors for the two soils were estimated to 0.71±0.13 and 0.64±0.08 kg N₂O-N/100 kg N for Flakkebjerg and Foulum, respectively (mean±standard deviation, n = 4). The values measured under Danish conditions were thus lower than the IPCC (2006) default emission factor for applied N (1 kg N₂O-N/100 kg N) and further the data suggest that increasing C contents may not inevitably lead to higher N₂O emissions, but other factors may influence the N₂O emissions as well.

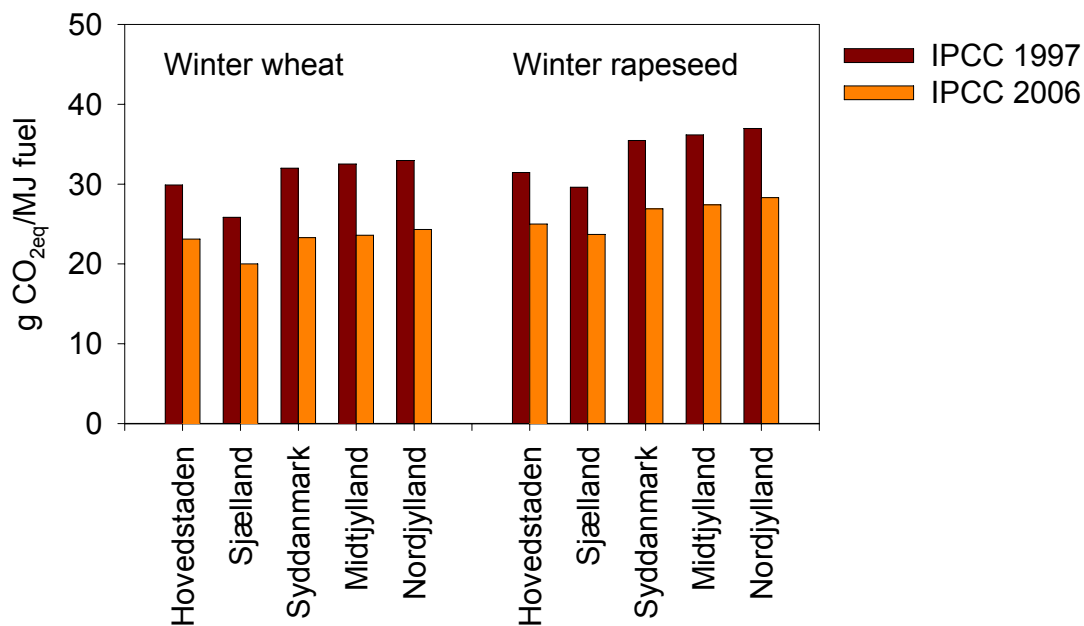


Figure 7. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N according to N₂O emission factors from IPCC (2006) and IPCC (1997).

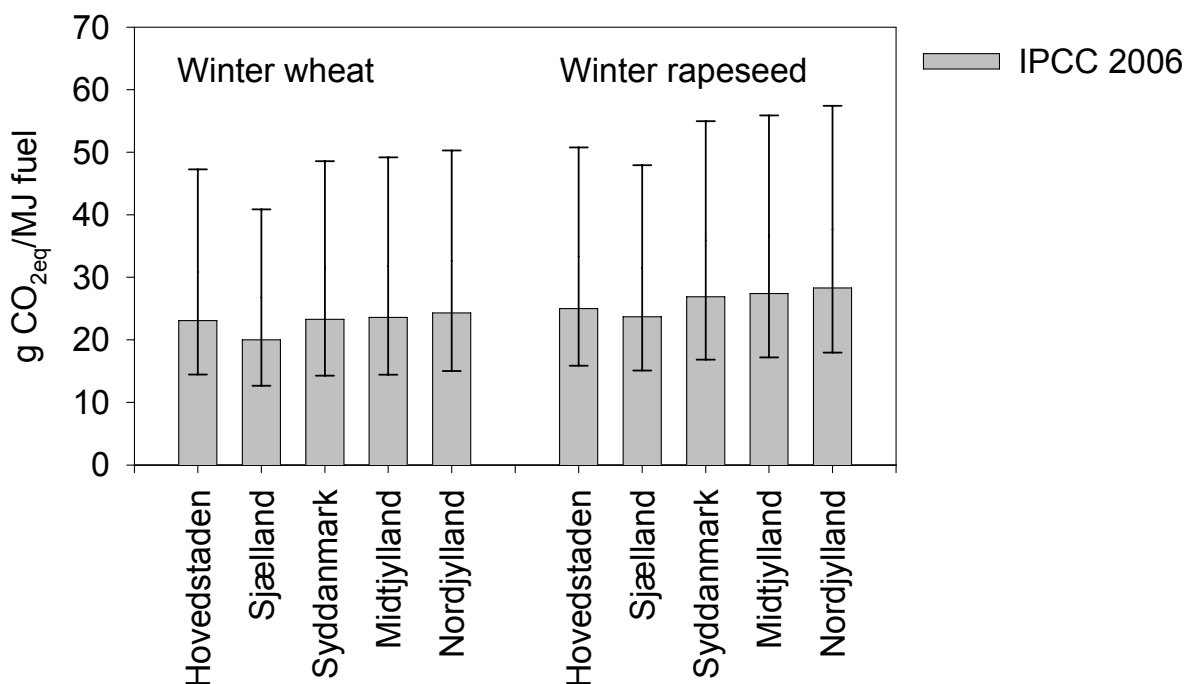


Figure 8. Greenhouse gas emissions (g CO_{2eq}/MJ fuel) from cultivation of winter wheat and winter rapeseed with synthetic fertilizer N according to N₂O emission factors and uncertainty estimates from IPCC (2006). Grey bars show the results for the default emission factors; lines indicate the ranges derived from the uncertainty range for the emission factors.

Concerning the role of organic soils, which have a higher IPCC emission factor for N₂O, Region Nordjylland is considered as an example. According to the Danish soil classification (the JB system) Region Nordjylland has the highest frequency of organic soils (classified as JB 11). As seen from Table 4 and 5 the cropping area on JB 11 represents 7.5% of the total area for winter wheat and 3.5% for winter rapeseed. These areas potentially could have a higher N₂O emission than calculated according to the IPCC emission factor of 1 kg N₂O-N/100 kg N. Thus, the default emission factor to estimate direct N₂O emissions from temperate organic crop and grassland soils is 8 kg N₂O-N/ha (IPCC, 2006) corresponding to 3721 kg CO_{2eq}/ha. However, the definitions of organic soils in the sense of the Danish JB system and the IPCC guidelines for calculation of N₂O emission are very different: In the Danish system soils classify as JB 11 (organic) if they have a C content higher than 5.9% (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 (this definition applies to soils that are never saturated with water for more than a few days). Therefore, it was not considered appropriate to treat the Danish JB 11 soils according to the IPCC emission factor for organic soils. Yet, if it was done nonetheless, the emission result for winter wheat in Region Nordjylland would increase by < 9%. The corresponding figure would be lower for winter wheat and (especially) for winter rapeseed in all other Regions.

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 N₂O emission from the soil. For example, changes in IPCC emission factors, such as those introduced between 1997 and 2006, resulted in changes in the emission results for the cropping systems corresponding to 24% (i.e., the emissions calculated for 2006 emission factors were 24% lower than calculated for 1997 emission factors). Likewise, the uncertainty range reported for the N₂O emission factors (IPCC, 2006) caused the final emission results to have a large uncertainty range. Better and more precise estimates of N₂O 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 N₂O, greenhouse gas emissions associated with production of N fertilizer had a major impact on the final emission results. Production of mineral fertilizers using best available technology (with catalytic removal of N₂O) has the potential to reduce the emission result for agricultural crops for biofuels as compared to N production at older European facilities. 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.

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, e.g., dedicated wheat varieties for ethanol production thus has a potential to lower the final emission results for biofuel production.

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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