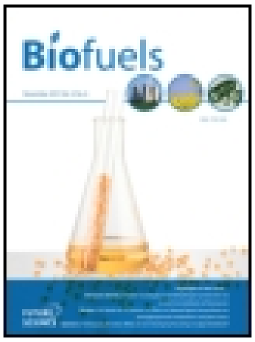

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EU sustainability criteria for biofuels: uncertainties in GHG emissions from cultivation

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EU sustainability criteria for biofuels: uncertainties in GHG emissions from cultivation

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Background: Cultivation of raw material represents a large proportion of biofuels´ GHG emissions. The EU renewable energy directive 2009/28/EC specifies a GHG emission default value for cultivation of biofuel raw material (23 g CO_2-e/MJ ethanol for wheat). The aim of this study was to quantify the uncertainty in GHG emissions for wheat cultivation in Sweden, considering uncertainty and variability in data at farm level. **Results**: Two levels of data collection at farm level were analyzed; simple (only yield and amount of N) and advanced (also including amounts and types of energy). The 2.5–97.5 percentile uncertainty for Swedish winter wheat was 20–27 g CO_2-e/MJ, which can be considered large in the context of the Directive's threshold of 23 g (to two significant figures). **Conclusion**: It is concluded that quantifying GHG emissions in order to regulate biofuels is a difficult task, especially emissions from cultivation, since these are biological systems with large variability.

EU sustainability criteria

Reduction of GHG emissions is one of the main reasons behind introducing biofuels as an alternative to fossil fuels; however, considerable GHG emissions occur in the production chain of biofuels from agricultural crops. In order to ensure that these GHG emissions are not excessive, limits and methods for calculating the emissions have been introduced into biofuel standards and legislation. In 2009, the EU adopted a climate–energy legislative package, including a Directive on promotion of the use of energy from renewable sources (Directive 2009/28/EC) [1]. One of the objectives of this Directive is to ensure that biofuels are produced in a sustainable manner and, for that purpose, it includes a set of sustainability criteria. Biofuels not in compliance with the criteria cannot be taken into account for the achievement of national targets and are not eligible for policy support.

The **EU sustainability criteria** include rules against biofuel cultivation on land with recognized high biodiversity value and high carbon stocks. Furthermore, the calculated GHG emission savings from the use of biofuel must be at least 35% compared with a reference fossil fuel. This GHG savings constraint will increase over time; for example, by the year 2017 the calculated saving must be 50%. For new bioenergy plants set up after 2017, the savings required will be 60% by 2018. The life cycle assessment (LCA) methodology for the GHG calculations is described in Annex V of the Directive. The method is attributional in its kind, and do not account for market-induced indirect effects [2].

The so-called economic operators are, according to the Directive 2009/28/EC, responsible for reporting GHG emissions for the biofuel (in Sweden the economic operators are defined as those who also are required to pay energy tax; e.g., sellers or distributors of biofuels). The economic operators are allowed to calculate GHG emissions from biofuels in two different ways: either **default values** given in the Directive can be used or actual values can be calculated.

Raw material cultivation in EU sustainability criteria

There are also special rules for GHG emissions from cultivation of raw material in the Directive. The most

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Key terms

EU sustainability criteria: The Directive on renewable energy (2009/28/EC) sets out sustainability criteria for biofuels in Articles 17, 18 and 19. These criteria are related to GHG savings, land with high biodiversity value, land with high carbon stock and agro-environmental practices. The criteria have applied since December 2010.

Default value: In the EU Directive defined as, *"a value derived from a typical value by the application of predetermined factors and that may, in circumstances specified in this Directive, be used in place of an actual value"*. The Directive provides a list of default values for the different production steps of biofuels.

Uncertainty: Three levels of uncertainty in GHG calculations can be identified: technical uncertainties connected to quality and appropriateness of data; methodological uncertainties connected to model layout and structure; and epistemological uncertainties connected to lack of knowledge of system behavior.

likely reason is because cultivation contributes to a large proportion of GHG emissions from biofuel production. In the Directive default values, cultivation comprises 33–88% of total ethanol GHG emissions, depending on chosen type of process fuel.

Economic operators can use the GHG default value for cultivation; for example, for wheat 23 g CO_2-e per MJ ethanol. However, the default value can only be used if the raw material is collected from a region in which the typical emission values, as established in the report submitted by each EU Member State to the EC by March 2010 (Article 19.2), has been proven to be equal to or lower than the default value. These Member State cultivation GHG reports are published on the EU transparency platform for public viewing [101]. The distinction between typical, average and actual values is important, but the Directive gives little guidance on this point, which is further described in the discussion section of this article.

According to Directive 2009/28/EC, the GHG emissions from crop cultivation must be expressed as g CO_2-e per MJ biofuel to two significant figures. However, emissions from cultivation are associated with major **uncertainties** [3–5]. One large uncertainty connected to ethanol production is N_2O emissions, which arise from the production and use of N fertilizers in cultivation of cereal raw material [6,7]. When the GHG calculations are complete, the uncertainty in cultivation emissions contributes greatly to the total uncertainty assessment of biofuels GHG reduction compared with fossil fuels, according to the Directive methodology [8,9].

▪ Uncertainty in biofuel GHG accounting

As pointed out in a recent study by McKone *et al.*, addressing uncertainty is one of the greatest challenges for LCA of biofuels [10]. Generally speaking, there are three levels of uncertainty in GHG calculations: technical uncertainties connected to quality and appropriateness of data; methodological uncertainties connected to model layout and structure; and epistemological uncertainties connected to lack of knowledge of system behavior [11,12]. Epistemological uncertainties are difficult to diminish; a reduction of epistemological uncertainties implies making known what one does not know. However, a general improvement of LCA practitioners awareness and understanding of certain key datasets could improve their ability to ask relevant questions, thereby reducing epistemological uncertainties [13].

In the case at hand, methodological uncertainties are reduced to a certain extent, since Directive 2009/28/EC gives some guidelines on methods and choice of data. There is, however, room for interpretation; for example, concerning the fossil reference, the allocation method and N_2O emissions from soil. A project for harmonization of the calculation method has been initiated to deal with these issues [102]. This does not, however, reduce the uncertainty that is due to limitations in the modeling process (e.g., ignoring indirect or nonlinear processes in inventory and impact assessment) [14].

Nevertheless, the technical uncertainties remain. Two types of technical uncertainties can be distinguished: measuring uncertainty and variability. Variability is an inherent property of a system and, unlike measuring uncertainty, it cannot be reduced by more accurate measurement [11,15]. In LCA of agricultural products, variability arises, for example, due to variations in yield between different regions and years, but also within regions in a particular year.

Measuring uncertainty arises from limited knowledge of the true value of a parameter and can be reduced by increased data collection and/or improved measurements. Reducing the measuring uncertainty in cultivation emissions can be done by collecting from farms; for example, yield levels, amount of fertilizers and pesticides applied, type of fertilizer and pesticide used, moisture content at harvest, amount and type of fuel used for drying, and fuel used for tillage and harvest. Some of these data are more crucial in calculating the GHG emissions correctly (e.g., type and amount of N fertilizer used), while others are less important (e.g., pesticide use). Furthermore, some data are easy to collect (e.g., Swedish farmers are required by law to keep records of pesticide use), while other data are more difficult to access (e.g., origin and emissions caused during the production of mineral fertilizers).

In the GHG calculation methodology laid down in the Directive, indirect effects are, at present, not included. The EC is, however, considering including indirect land use changes (ILUC). Direct land use change (DLUC) is connected to the field where biofuel feedstock is grown and occurs when a previous land use is converted to bioenergy crop production. The direct land use emissions are included in the Directive´s GHG calculation methodology and are connected to the same uncertainty as the other input parameters. ILUC, on the other hand, occurs when biofuel feedstock production displaces other types of production elsewhere on the globe. The quantification of ILUC is based on global economic modeling and the results from studies show large variations. Much of the variance in estimates of ILUC stems from model uncertainty and variability in the underlying processes. However, due to the complexity of the global economy, epistemological uncertainty is a major contributor to the uncertainty, and it is not likely that the large contribution from epistemic uncertainties will be reduced soon [16]. The inclusion of indirect changes is further treated in the discussion.

Proving low-emitting wheat

The Directive 2009/28/EC states (Annex V, part C, paragraph 6), "*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*" [1]. In other words, according to this statement economic operators may use values for larger or smaller regions, or even values from individual farms.

If a farmer (or group of farmers) can show that the cereal they produce has lower GHG emissions than the average cereal, this could be an economic advantage when they want to sell their crop. For biofuel producers it could also be an advantage to single out the 'low emitters', in order to improve the GHG profile of their fuel. It is, therefore, of interest to know whether lower emissions at farm level can be proven, considering the practical constraints of data collection and the uncertainties associated with GHG calculations.

Aim & objectives

The aim of the present study was to quantify the uncertainty in GHG emissions for wheat cultivation in Sweden when calculated using the methodology specified in Directive 2009/28/EC, considering the uncertainty and variability in data at farm level. The specific objective was to study how the uncertainty in results is affected when different amounts of agricultural input data are collected, and how that affects the confidence in comparing GHG emissions from wheat cultivation from different groups of farms. Wheat was chosen since it is the crop most commonly used for ethanol production in Sweden and because it has a default value in the EU Directive.

The outcomes of the study are expected to provide insights into the most influential parameters in determining the uncertainty of GHG emissions from cultivation and indicate to what extent crops deviate from the Directive default values, which is important information for policymakers. Another expected outcome from the study was recommendations on the level of data to be collected for GHG calculations, if actual values are to be calculated by economic operators. Finally, the study sought to determine the probability of selecting low-emitting farms in view of the uncertainties, which can be important information for economic operators and farmers.

Methodology

The calculations were performed according to the rules for calculating the GHG impact of biofuels described in the EU Renewable Energy Directive 2009/28/EC (Annex V), which in turn is based on an LCA approach. LCA is a methodology to quantify the environmental impact of a product or service. A distinction can be made between two types of LCA; attributional LCA study accounts the flows to and from a studied system but does not consider indirect effects; consequential LCA describes how flows will change in response to a possible decision and includes effects both inside and outside the life cycle of the studied system [2]. In this study, the methodology described in the Directive will be used, which is an attributional LCA approach that does not include indirect effects.

The uncertainty analysis included both 'measuring uncertainty', which describes the precision with which the parameters can be collected on a real-life farm, as well as 'variation', which describes the variation between farms due to differing farming systems, technical solutions and energy efficiencies.

System boundaries, functional unit & allocation

The system boundaries were cradle-to-farm gate; hence, calculating the emissions of GHG for wheat according to Directive 2009/28/EC. Only the contribution to global warming was considered, expressed as g CO_2-e/MJ ethanol produced, and the results were compared against the Directive default figure for wheat cultivation of 23 g CO_2-e/MJ biofuel.

According to Directive 2009/28/EC, the calculation of emissions from cultivation must 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*" (Annex V, part C, paragraph 6). In other words, all the inputs needed to produce dried winter wheat ready for ethanol production are accounted for. However, according to the Directive, emissions from the manufacture of machinery and equipment do not have to be taken into account. Concerning choice of data, the Directive provides little guidance other than that data should "*be obtained from independent, scientifically expert sources*" (preamble paragraph 83) [1].

Soil carbon change is only included in the GHG calculation method stated in the Directive if there is a land use change, for example, from forestry to agriculture and if the change took place after January 2008. It is further limited to only DLUC, that is, connected to the field where the biofuel crop is cultivated. Since most wheat cultivation in Sweden takes place on land that has been used for arable cropping for a long time, it does not fall under the LUC rule in the Directive and, consequently, direct LUC was not included in the present study; ILUC where also not included in the calculations, since it is not contained in the Directive methodology. At present, the EU is considering the inclusion of indirect LUC, which is further described in the discussion chapter of this article.

The functional unit was set to the cultivation of winter wheat for production of 1 MJ of ethanol, which requires 0.13 kg of winter wheat (14% moisture content) [17]. At the same time, 0.04 kg dried distillers grains with solubles (DDGS) (9% moisture content) is produced as a byproduct.

When more than one product arises in a production process, the environmental impact must be allocated over the products or the system must be expanded. According to Directive 2009/28/EC, allocation based on a lower heating value must be applied when calculating the GHG reduction of biofuels. In this case, the GHG emissions from wheat cultivation were divided between the end-products ethanol and DDGS, which is often used in animal feed. Allocation based on a lower heating value meant that 61% of cultivation emissions were allocated to ethanol and 39% to the byproduct DDGS. Straw from cereal production was considered a residue and was, therefore, not allocated any emissions; manure used as fertilizer followed the same principle and was not allocated any upstream emissions.

▪ Collection of data

Calculations of GHG emissions according to Directive 2009/28/EC were made for wheat cultivation in the year 2007 in five Swedish counties that produced more than 1.6 million metric tonnes of winter wheat in 2007, which represented 80% of the total Swedish winter wheat harvest that year [18]. No statistics on the individual farms that actually delivered wheat for ethanol production in 2007 were available. However, wheat yield data are collected annually by the Swedish national statistics agency from a number of selected farms throughout Sweden, and data on fertilizer amounts and types are collected biannually from another selection of farms [18,19]. The farms that were included in both the yield and fertilizer surveys in 2007 (making correlated data on yield and fertilizer amount available for these farms) were selected as representatives of the farms in a county delivering wheat for ethanol production. The number of farms concerned was 226, 146, 89, 58 and 57 in the counties Skåne, VästraGötaland, Östergötland, Södermanland and Uppland, respectively.

Six parameters have been shown to have a large influence on GHG emissions from wheat cultivation [6,20] and these parameters were included in the uncertainty analysis in this study **(Table 1)** [6,21,103]. Variation and uncertainty was expressed as the geometric standard deviation, since the distribution used is log-normal (for normal distribution the standard deviation would typically be used) or as a discrete distribution. The six influential parameters are: emissions factor for N_2O emissions from the field; yield; emissions factor for production of mineral N (expressed as kg CO_2-e/kg N); amount of N fertilizer (split into mineral and organic); amount of diesel used for field operations; and emissions factor for crop drying (expressed as kg CO_2-e/kg wheat, calculated based on the fuel used for drying). Data on parameters two to six can be collected at the farm level, while the N_2O emissions from the field need to be modeled. Remaining parameters needed to calculate the GHG emissions were kept constant **(Table 2)** [6,20,22,23].

In this study, real farm-level data on yield and amount of N fertilizer were used, by utilizing the raw-data used for calculating the average per county yield and fertilizer usage. The variation of these two parameters across farms was, hence, represented by the actual differences between real farms in the year of 2007. The measuring uncertainty of the yield and fertilizer usage was set to approximately ±2 and ±10%, respectively [6].

For the emissions of N_2O from soil, the IPCC emission factors and their corresponding uncertainty intervals were used [24]. An emissions factor of 0.01 (kg N_2O-N per kg N) is assigned by the IPCC to managed mineral soils for added N fertilizers and N in crop residues (the given uncertainty range of this factor is 0.003–0.03). This factor includes indirect emissions of N_2O, which arise from N leached from fields (factor 0.0075 [kg N_2O-N per kg N leaching] with an uncertainty range of 0.0005–0.025), and N that volatilizes as ammonia and is redeposited on the ground.

The variation in emissions from the production of mineral fertilizers was described by a discrete distribution indicating whether the fertilizers came from the company Yara International ASA, Norway (60%), Russia (24%) or other suppliers in the EU (16%). The emissions in these cases were set at 3.1, 8.1 and 7.8 kg CO_2-e/kg N, respectively. The uncertainty in these values was estimated at approximately ±20% (95% confidence interval [CI]), based on data supplied by Yara on variations between their production plants [103]. The same uncertainty was assumed for all fertilizers.

The amount of fuel used for field operations varies depending on the number and types of operations (~±50%; 99% CI), the soil clay content (~±50%; 99% CI), the driving manner (±30%; 95% CI), and the fit between tractor and machinery (~±10%; 95% CI). Hence, the total variation was approximately ±60% with a 95% CI (between 25 and 108 l/ha). The

Table 1. Parameters used in the calculation of GHG emissions from wheat cultivation for ethanol production with simple data collection and advanced data collection.

Parameter	Variation		Measuring uncertainty
	Simple data collection	Advanced data collection	Simple and advanced data collection
Yield	None[†]	None[†]	1.01 (±2%)[‡]
Amount of mineral N	None[†]	None[†]	1.05 (±10%)[‡]
Amount of organic N	None[†]	None[†]	1.05 (±10%)[‡]
Emissions from the production of mineral fertilizers	Discrete distribution 3.1 kg CO_2-e/kg N – 60% (Yara) 8.1 kg CO_2-e/kg N – 24% (Russia) 7.8 kg CO_2-e/kg N – 16% (EU)[¶]	None[§]	1.1 (±20%)[¶]
Amount of fuel for field operations	1.30 (± 60%) (25–108 l/ha)[††]	None[§]	1.05 (±10%)[‡‡]
Emissions from grain drying	Discrete distribution 16 g CO_2-e/kg grain – 25% (central drying) 21 g CO_2-e/kg grain – 63% (hot air farm drying) 11 g CO_2-e/kg grain – 12% (cold air farm drying)[§§]	None[§]	1.25 (±50%) for central drying, 1.1 (±20%) for hot on-farm drying; 1.2 (±35%) for cold on-farm drying[§§]

Variation and uncertainty expressed as the geometric standard deviation for a log-normal distribution (approximate percentage value corresponding to 95% confindence interval) unless otherwise stated.

[†] No variation since data on the parameter was collected from farms.

[‡] Data from [6].

[§] No variation. To simulate data collection from farms, a value was randomly selected for each farm.

[¶] Variation across production sites estimated using data from [103].

[††] See text for explanation.

[‡‡] Assumption based on using diesel consumption measuring equipment and careful accounting.

[§§] Distribution and variation across drying facilities based on [21] [Karlsson S & Nordenblad J, Pers. Comm.].

measuring uncertainty for diesel consumption was set at ±10%, which was an estimate based on having, for example, tractors equipped with fuel consumption meters combined with accounting that considered on which plots and operations fuel was used.

Emissions from drying wheat grain in order to make it storable vary with the amount of energy required and the type of fuel used. The amount of energy required varies with the moisture content of the wheat at harvest and the efficiency of the drying equipment. The

Table 2. Parameters with low influence on the end results that were kept constant in Monte Carlo simulations.

Parameter	Units	Mean value
Farm parameter		
Amount of P fertilizer	kg/ha	16[†]
Amount of K fertilizer	kg/ha	26[†]
Amount of seed	kg/ha	210[‡]
Amount of pesticides	kg active substance per ha	1.2[‡]
Transport parameter		
Fertilizer transport	km	439 (at sea) 360 (on road)[§]
Pesticide transport	km	8000 (at sea)[§]
Emission factor		
P fertilizer	kg CO_2-e/kg P	0.71[‡]
K fertilizer	kg CO_2-e/kg K	0.46[‡]
Pesticides	kg CO_2-e/kg active substance	5.4[‡]
Diesel	kg CO_2-e/l	2.7[‡]
Electricity	kg CO_2-e/MJ	0.028[¶]
Road transport	kg CO_2-e/ton km	0.065[‡]
Sea transport	kg CO_2-e/ton km	0.021[‡]

[†] Data from [6].

[‡] Data from [20].

[§] Distance between fertilizer plant in Finland and Sweden.

[¶] Nordic electricity mix in 2007 [22,23].

Key term

Monte Carlo simulation: Each input parameter in the GHG calculation is fitted with variation and uncertainty. Monte Carlo simulation, in which parameters are described with a probability distribution rather than one deterministic value and calculations, are repeated a large number of times, each time randomly drawing a parameter value and can be used to determine the uncertainty in the final result.

moisture content varies only slightly between counties for the same year and more between different years; here, the moisture content was set to 18% and kept constant. Based on data from the main actors in the grain trade in Sweden, 53% of the wheat was assumed to be dried at large central storage facilities and 47% on farms. Farm-based drying is fuelled by oil, while fuel types for central drying plants vary substantially (e.g., district heating, electricity and different types of fossil-based fuels). On-farm drying can be based on either cold or hot air and requires approximately 1.5–6 MJ of oil per kg and 0.7 MJ of electricity per kg water removed. For central drying facilities, actual data on amounts and type of fuels obtained from these facilities was used to establish the variation in GHG emissions for this type of drying **(Table 1)**.

Analytical methods

Variation between individual farms

To give an indication of the variation between individual farms due to the differences in yield and fertilizer application only, calculations of the GHG emissions according to the Directive, without taking further uncertainty into consideration, were performed. The calculations were based on yield and fertilizer data from the farms and mean values for all other parameters.

Uncertainty in GHG estimations of wheat delivered to ethanol plant

The uncertainty in GHG emissions per MJ of ethanol was quantified using **Monte Carlo (MC) simulation** [25]. In MC simulation, parameters are described by a probability distribution, rather than a single deterministic value, and the calculation of the GHG emissions is repeated a number of times (here 10,000) – each time randomly drawing a parameter value from the probability distribution. The result from an MC analysis consists of a number of possible outcomes (here 10,000) from the calculation, hence, giving a representation of the probability of different results from the GHG emissions calculation. The influential farm-level parameters used in the simulations are described in the section titled, 'Collection of data', and summarized in **Table 1**. All other data (summarized in **Table 2**) were kept constant in the MC simulations due to the low impact of these parameters on the final GHG emissions result [6].

In an ethanol plant, the wheat used in production is a mix of wheat from farms in each county, therefore, the GHG emissions uncertainty was calculated from this mix. The amount of wheat each county supplies to the ethanol plant was based on data from a Swedish ethanol plant in the city of Norrköping (Karlsson S, Pers. Comm.), however, data on how much each farm supplies are not available. Therefore, the contribution from each farm to the mix was calculated as a weighted fraction of the total wheat harvest from the individual farms. In other words, a farm with large production of wheat relative to the total wheat harvest in a county was also assumed to be a large supplier of wheat for ethanol production from that county.

To study how the uncertainty in results is affected when different amounts of agricultural input data are collected from farms, two levels of detail of data collection were examined. In the first case, called simple data collection (SDC), it was assumed that only data on wheat yield and the amount of N fertilizer (mineral and organic) applied was collected from the farms. In the SDC scenario, no information regarding the other three influential parameters (i.e., amount of diesel used for field operations, the amount and type of fuel used for drying, and origin of mineral fertilizer) was assumed to be available. Therefore, values for the variation in these parameters were applied, based on data from literature (see the section titled 'Classification of data' and **Table 1**). In the second case, known as advanced data collection (ADC), data on all five influential farm data parameters (i.e., yield, amount of fertilizer, origin of mineral fertilizers, diesel use and energy used for drying) were assumed to be collected, so all variation was set to zero. However, since no data for the amount of diesel used for field operations, the amount and type of fuel used for drying and the origin of mineral fertilizer was available directly from the farms in the data material used in this study, the collection of these parameters was simulated by randomly for each farm, drawing one value for these parameters, which was then used for that farm in all simulations. Measuring uncertainty was included in both ADC and SDC.

Effects of uncertainty in N_2O emissions

The N_2O emissions in the field were included in both SDC and ADC, using the methodology and uncertainty range as stated in the IPCC [24]. The IPCC emissions factors are set to be globally applicable and the large uncertainty ranges represent both the variation between – for example, different climate regions, soil types, weather conditions and the uncertainty in these emissions – due to the limited knowledge of these processes. Within these uncertainty ranges, N_2O emissions from the field are by far the largest source of GHG uncertainty from wheat cultivation [6]. However, it can be argued that since the present study was limited to only one climate region (Sweden), the uncertainty range is probably much smaller than that in the global figures supplied by the IPCC. Unfortunately, there is not enough knowledge or data available to determine a smaller uncertainty range applicable for variation within Sweden. In order to give an estimate of the uncertainty in the results caused by the uncertainty in N_2O emissions, the calculations were performed with N_2O uncertainty as specified by the IPCC [24], representing a maximum variation case, and entirely without N_2O uncertainty, representing a minimum uncertainty case.

Low-emitting farms

Finally, in order to study whether an ethanol producer could claim to have lower GHG emissions by selecting wheat from farms producing wheat with low emissions, the confidence in a comparison between wheat from the 20% most 'low-emitting wheat producers in a county' and 'all wheat producers from the specific county included in this study' was estimated. This estimation was made by pair-wise comparisons of the wheat mix GHG emissions resulting from MC simulation for these two groups of farms and by keeping correlated parameters constant. The 20% most low-emitting farms in each county were selected based on the deterministic wheat GHG values for each farm; the comparison was made using SDC to study whether this limited data collection strategy would be enough to differentiate between groups of farms.

Results

▪ Variation between individual farms

Table 3 shows the deterministic mean for GHG emissions from wheat cultivation for each of the five Swedish counties studied. This gives an indication of the variation between individual farms due to differences in yield and fertilizer application, without taking uncertainty into consideration (mean values for all other parameters were used). The variation between farms was large; for example, in Skåne the emissions varied between 10 and 33 g CO_2-e/MJ (range covering 95% of the farms). The calculations also showed that the mean values differed considerably between the counties. Two counties had a mean greather than the 23 g CO_2-e/MJ default value specified in Directive 2009/28/EC. The difference between counties was mainly due to differences in yield levels and partly to the amount of N fertilizer applied.

▪ Uncertainty in GHG estimations for wheat delivered to ethanol plants

Here we investigated the uncertainty in GHG emissions for a mix of wheat from different farms in a county, which is a representation of the actual situation in an ethanol plant. The results of the simulations for SDC and ADC in the different counties are presented in **Figure 1**. The uncertainty range is represented by the 2.5 and 97.5 percentiles of the results from the MC simulations. The uncertainty range in GHG calculations of wheat cultivation was mainly due to variation between farms with regards to the amount of N fertilizer applied, yield and the uncertainty in N_2O emissions from soil. In Directive 2009/28/EC, the default value for cultivation of winter wheat for ethanol production is 23 g CO_2-e/MJ ethanol. As can be seen, the mean value for Västra Götaland, Uppland and Södermanland exceeded this default.

In both the SDC and ADC cases, wheat from several farms was mixed, as in an ethanol plant. Compared with results from individual farms, the total uncertainty decreased, since high and low values cancelled one another out; for example, the outcome from the MC simulation for the mix of wheat from Skåne was reduced to a range of approximately 20–24 g CO_2-e/MJ, although uncertainty was included. The mean values for the deterministic individual farm calculations as presented in **Table 3** and those from the MC simulations **(Figure 1)** differed. This was due to the latter being the weighted sum of GHG emissions from wheat delivered to ethanol plants (weighted according to total amount of wheat produced per farm), while the deterministic farm means were unweighted.

Increasing the amount of data collected on farms (ADC case) had a minor effect on the uncertainty range across the counties **(Figure 1)**; in fact, there were larger differences between counties than between ADC and SDC.

▪ Effect of uncertainty in N_2O emissions

A large factor in the uncertainty was N_2O emissions, as we used the large uncertainty range given by the IPCC [24]. When N_2O uncertainty was excluded, the difference between SDC and ADC was more pronounced **(Table 4)**; for SDC, excluding N_2O uncertainty almost halved the range of the results in some counties, while for ADC the results were even more strongly affected. The percentage difference in range (SDC/ADC; **Table 4**) confirmed that the difference between the two data collection methods was larger when N_2O uncertainty was excluded.

▪ Low-emitting farms

One way for an ethanol producer to lower emissions could be to only use wheat produced on selected farms that have low emissions in the cultivation process. Due to the uncertainty in calculation methods and data, the question is whether this lower emission from a selection of low-emitting farms can be proven. We tested this by selecting the 20% of the farms with the lowest emissions in each county and comparing the wheat mix GHG emissions of this group of farms with that of all

Table 3. Deterministic GHG values for individual farms. The mean yield and mean amount of mineral and organic N fertilizers used are also specified.

Swedish county	Deterministic mean (g CO_2-e/MJ)	Interval[†] (g CO_2-e/MJ)	Mean yield (kg/ha)	Mean amount mineral N (kg/ha)	Mean amount organic N (kg/ha)
Skåne	22	10–33	7500	153	22
Västra Götaland	26	12–38	5700	139	37
Östergötland	23	15–33	6500	123	40
Uppsala	21	10–32	5900	111	26
Södermanland	24	8.3–32	5400	106	39

[†] 2.5 and 97.5 percentiles of the farms; that is, the extreme values are excluded. In this range, 95% of the simulated results are included.

farms in the county; this was performed using pair-wise comparisons of the outcomes from the MC simulations for these two groups. It was found that the probability was 100% for all counties using SDC and not taking N_2O uncertainty into account, and 98% or higher when N_2O uncertainty was included. It is debatable whether the emissions factor for N_2O should be seen as correlated or not (and, hence, whether N_2O uncertainty should be included or not) in comparisons between farms. On the one hand, climate conditions are the same for the wheat in the two groups, since it is grown in the same region, which would justify not including N_2O uncertainty in the comparison [26]. On the other hand, N_2O emissions can vary greatly, even within the same region and under the same climate conditions, due to other (uncorrelated) factors, such as soil conditions, which would justify including N_2O uncertainty in the comparison. However, in our case, both including the N_2O uncertainty (hence, possibly overestimating the uncertainty) and excluding the N_2O uncertainty (hence, possibly underestimating the uncertainty) gave a high probability (more than 98% for all counties) that the wheat mix from the low-emitting farms had significantly lower emissions in cultivation.

Figure 2 shows the outcome from the MC simulations for the group of farms with low emissions and the group of all farms in the Skåne region. As is clear from the diagram, the wheat mix GHG emissions from these two groups were well separated, although uncertainty information was included.

Discussion

The variations between farms were very large; for example, within the same year and region they could vary by a factor of 3 **(Table 3)**. Variations between regions were smaller but not negligible, and three of the five counties had a deterministic mean above the EU default value of 23 g CO_2-e/MJ **(Table 3)**. Even with ADC, there are uncertainties associated with the results and a possibility that wheat exceeding the default given by the EU may be used in biofuel production.

The uncertainty calculations in the SDC and ADC cases were designed to represent the variability in

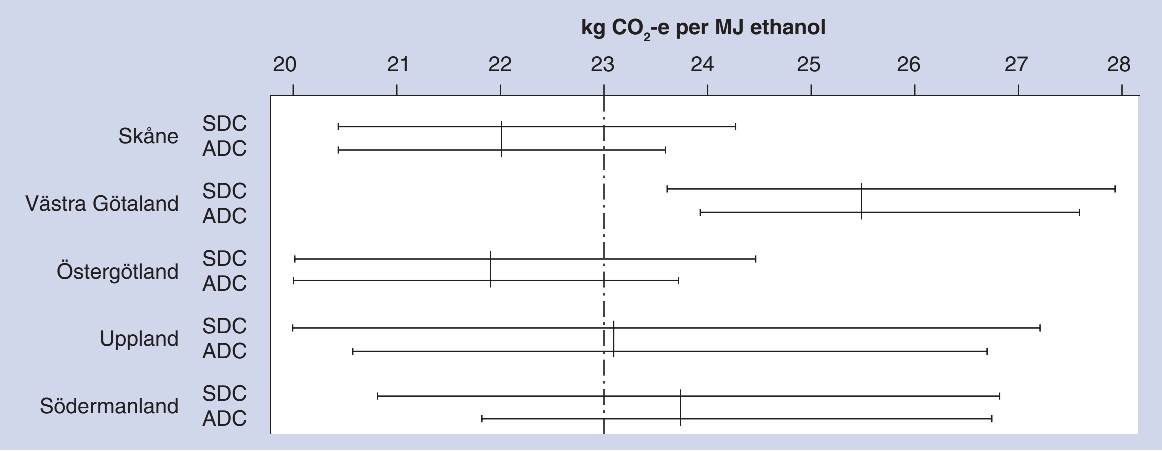

Figure 1. Mean values and uncertainty range in GHG emissions from wheat production (g CO_2-e/ MJ ethanol) in 2007 in five counties in Sweden. In Directive 2009/28/EC, the default value for winter wheat is set at 23 g CO2-e/MJ ethanol.

ADC: Advanced data collection; SDC: Simple data collection.

GHG emissions from cultivation of wheat delivered to an ethanol production plant. With the current uncertainty in N_2O emissions, reduction of uncertainty by collecting more data is small; for ADC the range

Table 4. Values, ranges and percentage difference in range of emissions for simple data collection and advanced data collection, including and excluding uncertainty in N_2O emissions.

Swedish county	N_2O uncertainty	Mean	GWP SDC ($g\ CO_2$-e/MJ)		GWP ADC ($g\ CO_2$-e/MJ)		Difference in range (SDC/ADC) (%)
			2.5–97.5 percentiles	Range	2.5–97.5 percentiles	Range	
Skåne	Included	22	20.4–24.3	3.9	20.4–23.6	3.2	18
	Excluded		21.2–23.4	2.2	21.5–22.1	0.6	73
Västra Götaland	Included	26	23.6–27.9	4.3	23.9–27.6	3.7	13
	Excluded		24.5–26.8	2.3	25.0–25.7	0.7	72
Östergötland	Included	22	20.0–24.4	4.4	20.0–23.7	3.7	15
	Excluded		20.9–23.2	2.3	21.3–22.0	0.7	71
Uppsala	Included	23	20.0–27.2	7.3	20.6–26.7	6.1	16
	Excluded		21.3–25.4	4.1	22.5–23.8	1.3	68
Södermanland	Included	24	20.8–26.8	6.0	21.8–26.7	4.9	18
	Excluded		21.9–25.3	3.3	23.5–24.6	1.1	68

ADC: Advanced data collection; GWP: Global warming potential; SDC: Simple data collection.

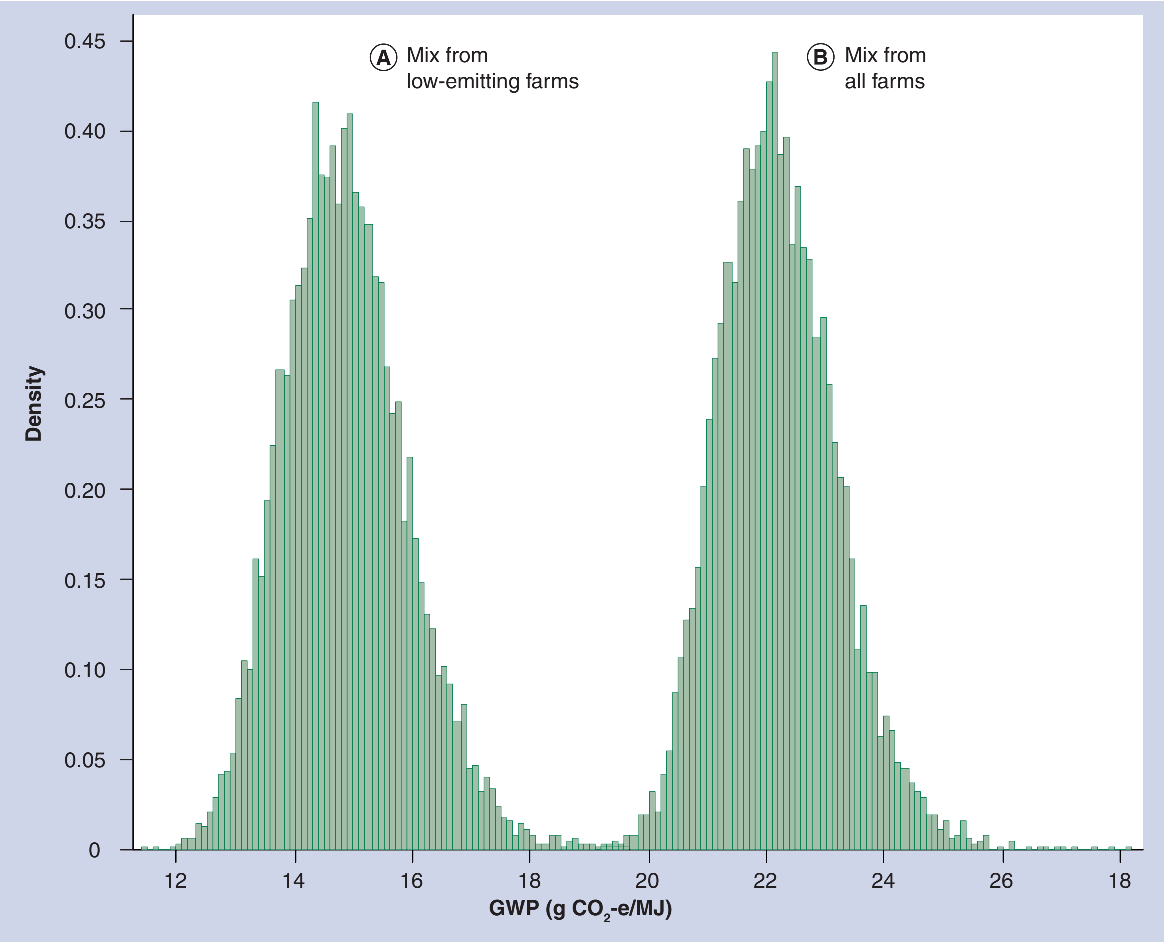

Figure 2. GHG emissions results for Skåne (county simple data collection including N_2O uncertainty). For cultivation of a mix of wheat from all farms **(B)** and a mix of wheat from the 20% most low-emitting farms **(A)**.

is only reduced by 13–18% compared with SDC in the different regions **(Figure 1 and Table 4)**. This is not large enough to justify the effort of additional data collection. The main cause of uncertainty is that of N_2O emissions, which masks increases ADC precision. However, if future improvements in N_2O models can reduce uncertainty in N_2O emissions values, ADC can give considerable improvements in the precision of GHG emissions calculations.

The variability in yields between farms was a major cause for the uncertainty and the reason for the variability is difficult to establish. In general, there is a direct positive correlation between the amount of N applied and yield level; however, yield is often influenced by many other factors, such as weather conditions during the growing season, soil texture, weed pressure, soil phosphate level and disease pressure [27], making any type of modeling very difficult [28]. This implies that data on N and yield levels can not be generalized, but that actual data are needed for the calculation of GHG emissions according to the Directive methodology.

As previously mentioned, each Member State in the EU had to report to the EC by March 2010 whether the typical value of GHG emissions from cultivation is below the default values in the Directive (Article 19.2). According to the Swedish Member State report to the EC on GHG, Swedish winter wheat is below the stated default values for GHG emissions in the studied counties [20]. The study by Ahlgren *et al.* had some limitations; for example, the use of manure was not included [20]. Another reason for the discrepancy between the Member State report and the results in the present study may be the emissions factor used for production of mineral N fertilizer. Ahlgren *et al.* used a value of 2.9 kg CO_2-e/kg N, while in the present study three different emissions factors were used **(Table 1)** [10]. Most importantly, however, the Ahlgren *et al.* study was deterministic and data were chosen to represent a typical farm in each county, not an average of all farms in a county [10]. This was because Directive 2009/28/EC makes a distinction between typical values (to be used in Member State reports), actual values and average values (to be used by economic operators). A typical value is defined in the Directive (Article 2) as, "*an estimate of the representative greenhouse gas emission saving for a particular biofuel production pathway*," while in Ahlgren *et al.* [20] it is interpreted as an estimate of the representative GHG emissions from cultivation in a region. While there is no definition of an average value, an actual value is "*the greenhouse gas emission saving for some or all of the steps of a specific biofuel production process calculated in accordance with the methodology laid down in part C of Annex V*" [1].

However, the Directive does not specify how typical, actual or average values should be obtained considering space and time factors. For instance, data from one individual farm during one specific year could be considered as actual data, but also as average data, since the wheat is likely to be a mix harvested from different fields within the farm. Even the harvest from one field could, in its extreme, be considered an average, since there are variations within each field. An average value might also very well be considered a typical value. In conclusion, there is no clear distinction between typical, average and actual values and the Directive does not clarify on this point.

Variation in time is also important. In a study by Röös *et al.*, GHG emissions from winter wheat cultivation were calculated for 4 years and the results showed large variations between years due to natural variation [6]. The GHG results can also change over time due to other factors, such as new technologies and better management; for example, the emissions from production of N fertilizers have been lowered during recent decades due to improved energy efficiency, while in recent years the use of catalytic filters to remove N_2O from flue gas has given large emissions reductions. The number of years used for calculating the typical or average value can, in other words, be of great influence for the resulting GHG emissions.

In addition to uncertainty connected to data described in this study, a further problem with the current EU regulation of the GHG emissions of biofuels is the exclusion of indirect effects. Indirect effects can be: market induced, for example, an increased production of bioenergy affects the price of agricultural inputs, which, in turn, will affect the way farmers use their land; or nonmarket induced, such as broader behavioral change and technological learning. Another indirect effect of biofuel production is that the demand of fossil fuels will be reduced, which can decrease the price of fossil fuels and, in turn, lead to increased use of fossil fuels. In other words, it is not certain whether the production of 1 MJ biofuel will result in 1 MJ less fossil fuel use [29]. Indirect effects are difficult to quantify and tend to be very uncertain, but can potentially be large enough to change the carbon balance.

In the EU it is widely recognized that ILUC GHG emissions need to be accounted for in the assessment of the carbon balance of biofuels and the EC is currently working on ways to include ILUC in the Directive sustainability certification system [30]. The EC considers that, although affected by large uncertainty dependent on how the modeling is performed [16,31,32], the magnitude of potential GHG emissions due to ILUC is large enough to change the carbon balance of most biofuels. However, accounting for ILUC in the EU regulation of biofuels is proving a challenging task for policymakers, as evidenced by slow progress and long delays. The ILUC issue has attracted enormous attention, not only of policymakers and environmental NGOs, but also of the research community, with the publication of hundreds of studies in the last 4 years. Although we agree with the need to account for the ILUC of biofuels in the EU regulation, the results of this study suggest that work on the direct GHG emissions of biofuels should progress in parallel with improvements of the methodology for accounting for the indirect GHG emissions. If ethanol producers start choosing wheat from low-emitting farms (as previously suggested), wheat not selected for biofuel production will still be used for other purposes, so the total emissions from wheat cultivation in a given year will remain the same. On the other hand, market demands on low GHG emissions might induce farmers to try to lower their emissions, leading to an overall positive indirect effect. However, the only way to make sure high emitting crops are not relocated to other sectors, is by applying the same regulatory requirements to all products of farming activities in the EU including food, feed, fiber and energy products.

Conclusion

The 2.5–97.5 percentile uncertainty for Swedish winter wheat was 20–27 g CO_2-e/MJ, which can be considered large in the context of the Directive's threshold of 23 g to two significant figures. Furthermore, in the discussion it is pointed out that the Directive does not give clear guidance on how input data should be limited in space and time, which adds to the uncertainty. We conclude that it is a difficult task to quantify GHG emissions in order to regulate biofuels, and especially difficult with emissions from cultivation, since these are biological systems with large variability. However, even if the current methodology for the calculation of GHG emissions of the EU Directive cannot be improved as to completely resolve all technical uncertainties, we conclude that the methodology could be improved by clearly distinguishing between typical, average and actual values. We also conclude that, by applying the same regulatory requirements to all products of farming activities in the EU, including food, feed, fiber and energy products, we can avoid relocating high-emitting crops to other sectors. The results of this study also suggest that work on the direct GHG emissions of biofuels should progress in parallel with improvements of

Executive summary

Background

- The EU has implemented sustainability requirements for biofuels, including regulation of GHG emissions from cultivation of raw material; however, calculation of GHG emissions from farming activities is connected with uncertainty.
- The aim of this study was to quantify the uncertainty in GHG emissions for wheat cultivation in Sweden, considering uncertainty and variability in data at farm level.

Methodology

- The GHG calculations were performed according to the rules described in the EU Renewable Energy Directive 2009/28/EC, which is an attributional life cycle assessment approach.
- The uncertainty in GHG emissions per MJ of ethanol was quantified using Monte Carlo simulation. Two different levels of farm data collection were analyzed, simple and advanced.

Results

- The mean values for cultivation of wheat varied between 22 and 26 g CO_2-e per MJ ethanol, indicating that the default value of 23 g CO_2-e per MJ is relevant for Swedish conditions.
- However, the uncertainty range in GHG emissions calculations for winter wheat cultivation can be considered large in the context of the Directive's threshold to two significant figures. The main reason for uncertainty was the variation between farms in obtained yields and the amount of N fertilizers used, and the uncertainty associated with N_2O emissions from soil. The 2.5–97.5 percentile variation for Swedish winter wheat was 20–27 g CO_2-e/MJ, even when advanced data collection was used.
- By selecting farms with low emissions in a region, the GHG emissions in ethanol production can be significantly reduced compared with using a mix of wheat from all farms in the region.

Discussion & conclusion

- We conclude that it is a difficult task to quantify GHG emissions in order to regulate biofuels and especially difficult with emissions from cultivation, since these are biological systems with large variability.
- However, even if the current methodology for the calculation of GHG emissions of the EU Directive cannot be improved as to completely resolve all technical uncertainties, we conclude that the methodology could be improved by clearly distinguishing between typical, average and actual values.
- Since the Directive applies to only GHG emissions from crops used for biofuels, high-emitting crops might be relocated to other sectors, making no difference in the total GHG emissions. We conclude that this could be avoided by applying the same regulatory requirements to all products of farming activities in the EU including food, feed, fiber and energy products.
- The results of this study also suggest that work on the direct GHG emissions of biofuels should progress in parallel with improvements of the methodology for the calculation of the indirect GHG emissions.

the methodology for inclusion of the indirect GHG emissions.

Future perspective

The areas for which GHG regulations are used is expanding; that is, there are increasing suggestions for detailed regulation of solid bioenergy and bio-based products. However, the uncertainty in bioenergy GHG calculations is large. It can be discussed whether policy that requires detailed calculations of GHG emissions is an appropriate way forward. The uncertainty can be reduced, especially if N_2O emissions can be more accurately quantified. Results from future field measurements on N_2O may demand a change in the methods used to estimate N_2O from bioenergy production, which would have a large impact on total calculated GHG emissions. However, inclusion of ILUC effects on GHG emissions, which is under discussion both in science and policy, can have an even larger impact on the uncertainty in bioenergy GHG calculations.

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No writing assistance was utilized in the production of this manuscript.

References

Papers of special note have been highlighted as:

- ▪ of interest
- ▪▪ of considerable interest

1 EC. *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*. EC, Brussels, Belgium (2009).

2 Brander M, Tipper R, Hutchison C, Davis G. Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. *Ecometrica Press. Technical Paper,* April (2009).

3 Freibauer A. Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. *Eur. J. Agro.* 19(2), 135–160 (2003).

4 Gibbons JM, Ramsden SJ, Blake A. Modelling uncertainty in greenhouse gas emissions from UK agriculture at the farm level. *Agric. Ecosyst. Environ.* 112(4), 347–355 (2006).

▪ **Studies cost–effective measures to lower the GHG emissions at farm level, assessing the certainty of the estimations using Monte Carlo simulation.**

5 Hastings AF, Wattenbach M, Eugster W, Li C, Buchmann N, Smith P. Uncertainty propagation in soil greenhouse gas emission models: an experiment using the DNDC model and at the Oensingen cropland site. *Agric. Ecosyst. Environ.* 136(1–2), 97–110 (2010).

6 Röös E, Sundberg C, Hansson P-A. Uncertainties in the carbon footprint of refined wheat products: a case study on Swedish pasta. *Int. J. Life Cycle Assess.* 16(4), 338–350 (2011).

▪▪ **Studies uncertainty in Swedish wheat-based pasta GHG footprint and has many connections to the present paper.**

7 Soimakallio S, Mäkinen T, Ekholm T, Pahkala K, Mikkola H, Paappanen T. Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – dealing with the uncertainties. *Energy Policy* 37(1), 80–90 (2009).

8 Soimakallio S, Koponen K. How to ensure greenhouse gas emission reductions by increasing the use of biofuels – suitability of the European Union sustainability criteria. *Biomass Bioenergy* 35(8), 3504–3513 (2011).

9 Edwards R, Szekeres S, Neuwahl F, Mahieu V. *Biofuels in the European Context: Facts and Uncertainties*. EC Joint Research Centre, Brussels, Belgium (2009).

10 McKone TE, Nazaroff WW, Berck P *et al.* Grand challenges for life-cycle assessment of biofuels. *Environ. Sci. Technol.* 45(5), 1751–1756 (2011).

11 Björklund A. Survey of approaches to improve reliability in LCA. *Int. J. Life Cycle Assess.* 7(2), 64–72 (2002).

▪ **Good introduction to uncertainty and variability in life cycle assessment.**

12 Spielmann M, Scholz R, Tietje O, Haan P. Scenario modelling in prospective LCA of transport systems. Application of formative scenario analysis. *Int. J. Life Cycle Assess.* 10(5), 325–335 (2005).

13 Von Bahr B, Steen B. Reducing epistemological uncertainty in life cycle inventory. *J. Clean. Prod.* 12(4), 369–388 (2004).

14 Zamagni A, Buttol P, Porta P *et al. Critical Review of the Current Research Needs and Limitations Related to ISO-LCA Practice. Deliverable D7 of Work Package 5 of the CALCAS Project*. The Italian National Agency on new Technologies, Energy and the Environment, Rome, Italy (2008).

15 Johnson DR, Willis HH, Curtright AE, Samaras C, Skone T. Incorporating uncertainty analysis into life cycle estimates of greenhouse gas emissions from biomass production. *Biomass Bioenergy* 35(7), 2619–2626 (2011).

▪ **Good introduction to uncertainty and variability in life cycle assessment.**

16 Plevin RJ, O´Hare M, Jones AD, Torn MS, Gibbs HK. Greenhouse gas emissions from biofuels. Indirect land use change are uncertain but may be much greater than previously estimated. *Environ. Sci. Technol.* 44(21), 8015–8021 (2010).

17 Bernesson S, Nilsson D, Hansson PA. A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions. *Biomass Bioenergy* 30(1), 46–57 (2006).

18 Statistics Sweden. *Production of Cereals, Dried Pulses, Oil Seed Crops, Potatoes and Temporary Grasses in 2007. Final Statistics*. Swedish Board of Agriculture, Gothernberg, Sweden (2008).

19 Statistics Sweden. *Use of Fertilizers and Animal Manure in Agriculture in 2006/07.*

Final Statistics. MI 30 SM 0803. Swedish Board of Agriculture, Gothernberg, Sweden (2008).

20 Ahlgren S, Hansson P-A, Kimming M, Aronsson P, Lundkvist H. *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).* Swedish University of Agricultural Sciences, Uppsala, Sweden (2011).

21 Jonsson N. *Uppdatering av Gårdens Spannmålstork. Ett Projekt Utfört på Uppdrag av SLA. JTI – Institutet för Jordbruks – Och Miljöteknik.* Swedish Institute of Agricultural and Environmental Engineering, Stockholm, Sweden (2006).

22 Uppenberg S, Alemark M, Lindfors L-G *et al.* Miljöfaktabok för bränslen. Del 2. Bakgrundsinformation och Teknisk bilaga. In: *IVL Rapport B1334B-2.* Swedish Environmental Research Institute, Stockholm, Sweden (2001).

23 Swedenergy. The electricity year 2007. Underlag för beräkning av Nordisk elmix för ursprungsmärkning av el år 2007, Appendix 2. In: *Vägledning angående ursprungsmärkning av el 2007.* Swedenergy, Stockholm, Sweden (2008).

24 *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme (Volume 4).* Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. (Eds). IPCC, London, UK (2006).

25 Rubinstein RY, Kroese DP. *Simulation and the Monte Carlo Method.* Wiley-Interscience, NY, USA, 707 (2008).

26 Chatterton J, Audsley E, Williams AG. Demonstrating significant differences in carbon-footprinting, despite N_2O. *Int. J. Life Cycle Assess.* 16(2), 102–105 (2010).

27 Plant R, Mermer A, Pettygrove G *et al.* Factors underlying grain yield spatial variability in three irrigated wheatfields. *Trans. Am. Soc. Agric. Eng.* 42(5), 1187–1202 (1999).

28 Landau S, Mitchell RC, Barnett V, Colls JJ, Craigon J, Payne RW. A parsimonious, multiple-regression model of wheat yield response to environment. *Agric. For. Meteorol.* 101(2–3), 151–166 (2000).

29 Fargione JE, Plevin RJ, Hill JD. The ecological impact of biofuels. *Ann. Rev. Ecol. Evol. System.* 41(1), 351–377 (2010).

30 EC. *Report from the Commission on Indirect Land-Use Change Related to Biofuels and Bioliquids.* EC, Brussels, Belgium (2010).

31 Wicke B, Verweij P, Van Meijl H, Van Vuuren DP, Faaij APC. Indirect land use change: review of existing models and strategies for mitigation. *Biofuels* 3(1), 87–100 (2011).

32 Mullins KA, Griffin WM, Matthews HS. Policy implications of uncertainty in modeled life-cycle greenhouse gas emissions of biofuels. *Environ. Sci. Technol.* 45(1), 132–138 (2011).

■■ **Studies the uncertainty in biofuel GHG emissions, including indirect land use changes, using Monte Carlo simulation.**

▪ Websites

101 EC Renewable Energy Transparency Platform. Emissions from cultivation (Article 19[2]). http://ec.europa.eu/energy/renewables/transparency_platform/emissions_en.htm (Accessed 1 February 2012)

102 BioGrace. Harmonization of greenhouse gas (GHG) emission calculations of biofuels throughout the European Union. www.biograce.net (Accessed 1 February 2012)

103 Yara. The carbon footprint of fertilizers. www.yara.com/sustainability/climate/index.aspx (Accessed 1 February 2012)