Interpretation of LCA results:

A Worked Example on a CO_2 to Fertilizer Process

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Published April 2020
This work is available under DOI 10.3998/2027.42/154990
and can be downloaded via http://hdl.handle.net/2027.42/154990

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Foreword

Climate change is one of the largest challenges of our time. It is proven that excess amounts of carbon dioxide that humanity has added to the atmosphere plays a key role, and left unaddressed, this will alter ecosystems and fundamentally change life as we know it. Under the auspices of the UN Framework Convention on Climate Change and through the Paris Agreement, there is a commitment to keep global temperature increase to well below two degrees Celsius. Meeting this goal will require a variety of strategies including increased renewable power generation and broad scale electrification, increased energy efficiency, and carbon-negative technologies. Carbon-negative technologies serve two purposes, as a climate mitigation tool near term, and to create a new carbon economy that recycles carbon over the long term- balancing emissions of still essential industrial sectors such as cement and steel. Overall, carbon-negative technologies are a valuable strategy in an overall portfolio of approaches to stabilize the atmospheric carbon dioxide concentration at a level that supports human life on Earth.

Increased attention is being paid to the notion that carbon dioxide can become a valuable resource instead of being a waste product with severe negative consequences to the earth's climate. New technologies, new use cases, interest from the investment community, and growing legislative support poise the use of a carbon dioxide feedstock as a viable economic and societal opportunity.

But not all that glitters is gold! Thorough assessment of the environmental and economic benefits of new technologies is paramount prior to deployment. Transparent and consistent life cycle assessments and techno-economic assessments must provide unbiased information to decision makers to enable sound decisions on investments, deployments, and public support for such.

International demand from government bodies, industry, investors, non-profits, and researchers for harmonized approaches to conduct life cycle assessments and techno-economic assessments for carbon dioxide utilization led us to coordinate and fund an international effort to develop and disseminate Guidelines for TEA & LCA for CO_2 Utilization. First published in 2018, these Guidelines have found widespread attention and use. A growing list of case studies, and worked examples, is made available to illustrate how to use these Guidelines.

We hope that this case study will be useful to you and we will be grateful for any feedback!

April 2020, Volker Sick, Global CO_2 Initiative

Abbreviations

ADP: Abiotic depletion potential

AP: Acidification potential

EP: Eutrophication potential

FAETP: Freshwater aquatic ecotoxicity potential

GHG: Greenhouse gases

GWP: Global warming potential

HTP Human toxicity potential

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

MAETP: Marine aquatic ecotoxicity potential

NPK: Nitrogen, phosphorus, potassium

POCP: Photochemical ozone creation potential

ODP: Ozone layer depletion potential

TETP: Terrestic ecotoxicity potential

TRL: Technology readiness level

Contents

This worked example is part of a series of worked examples produced in support of the "Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization". These guidelines, further worked examples and other associated documents can be found online at:

https://deepblue.lib.umich.edu/handle/2027.42/145423

More details on the Global CO_2 initiative can be found online at:

https://www.globalco2initiative.org/

*This worked example can be read independently of or in conjunction with:

"Building an LCA inventory: A Worked Example on a CO_2 to Fertilizer Process"

1 Introduction

This study is a worked example targeted at a general audience that wishes to understand how to apply the Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization (Zimmermann, et al., 2018) (from now on referred to as only "the guidelines" in this work). The results should not be used in comparative assertions by the public. The guidelines explain each part of an LCA with practical recommendations and suggestions on how to achieve a robust, reliable and repeatable LCA. In this worked example a focus is placed on the interpretation section and how to apply what is recommended in the guidelines to a practical case. The product under assessment has already gone through the initial LCA stages (goal and scope, inventory and impact assessment) in another worked example in this series, titled Inventories: worked example for CO_2 based fertilizer production (this can be found in the repository mentioned on the prior page). The results from the impact assessment section are used in this worked example for further analysis focused on interpretation.

The CO_2 utilization product is a new bio-fertilizer that the stakeholder wishes to introduce to the market. This biofertilizer relies on CO_2 captured from anaerobic digestion that reacts with aqueous ammonia and calcium nitrate to produce a fertilizer with 10 % N, 0.6 % P and 0.3 K content. The CO_2 based product is compared against the following fertilizers: Nitram® (33.5 N) (CF Fertilizers UK limited, 2019), Yara mila (NPK 15 15 15) (Yara, 2019), Fertilizer Europe N (33.5 N) (Fertilizers Europe, 2000), Fertilizer Europe NPK (NPK 15 15 15), cattle manure and mineral fertilizer from a commercial LCI database (Ecoinvent version 3.4) (Nemecek, 2007). From this, data from different sources was collected to create eighteen different life cycle inventories (Shown in Table 1). These inventories and their impact results are the basis for this worked example. Further details on the products under assessment and the initial LCA stages can be found in the worked example titled "Inventories: worked example for CO_2 based fertilizer" mentioned above.

Table 1 - Assessment scenarios for fertilizer production and land application

Assessment scenario	Anaerobic digestion	Fertilizer production	Field production
1A	Stakeholder data	Stakeholder data	Literature mix data
1B	Stakeholder data	Stakeholder data	Ecoinvent dataset, mineral fertilizer
1C	Stakeholder data	Stakeholder data	Fertiliser Europe carbon footprint
1D	Ecoinvent data	Stakeholder data	Literature mix data
1E	Ecoinvent data	Stakeholder data	Ecoinvent dataset, mineral fertilizer
1F	Ecoinvent data	Stakeholder data	Fertiliser Europe carbon footprint
2A	NA	Fertiliser Europe carbon footprint	Fertiliser Europe carbon footprint
2B	NA	Nitram carbon footprint	Literature mix data
2C	NA	Nitram carbon footprint	Ecoinvent dataset, mineral fertilizer
2D	NA	Nitram carbon footprint	Fertiliser Europe carbon footprint
3A	NA	Fertiliser Europe carbon footprint	Fertiliser Europe carbon footprint
3B	NA	Yara carbon footprint	Literature mix data
3C	NA	Yara carbon footprint	Ecoinvent dataset, mineral fertilizer
3D	NA	Yara carbon footprint	Fertiliser Europe carbon footprint
4A	NA	Literature mix-data	Literature mix data
4B	NA	Ecoinvent dataset	Ecoinvent dataset, organic fertilizer
5A	NA	Ecoinvent dataset	Literature mix data
5B	NA	Ecoinvent dataset	Ecoinvent dataset, mineral fertilizer

The following sections focus on sensitivity issues when using multiple LCIs, boundaries and scenarios for an LCA study for CO_2 utilization technologies.

2 Assessment routes for multiple life cycle inventories and assumptions

To arrive at the interpretation stage, a series of assumptions and decisions have already been made throughout the previous LCA stages. It can be easy to lose track of these decisions if not careful and thus complicate the interpretation stage. For this worked example where the focus is fertilizer production, there are three different application rates of the product to soil. For each application rate there are eighteen life cycle inventories that could be used for interpretation. For the CO_2 based fertilizer (the main product under assessment) there is still limited data for field usage (and associated usage emissions) as the product is still being tested in field trials. Preliminary field data results suggest that the CO_2 based fertilizer is comparable to a commercial ammonium nitrate fertilizer, particularly Nitram® (that was also used as a control in the field trials). However, no further data on application rates was available and therefore three application rates scenarios were considered (see Figure 1).

The three application rates are described on the following page.

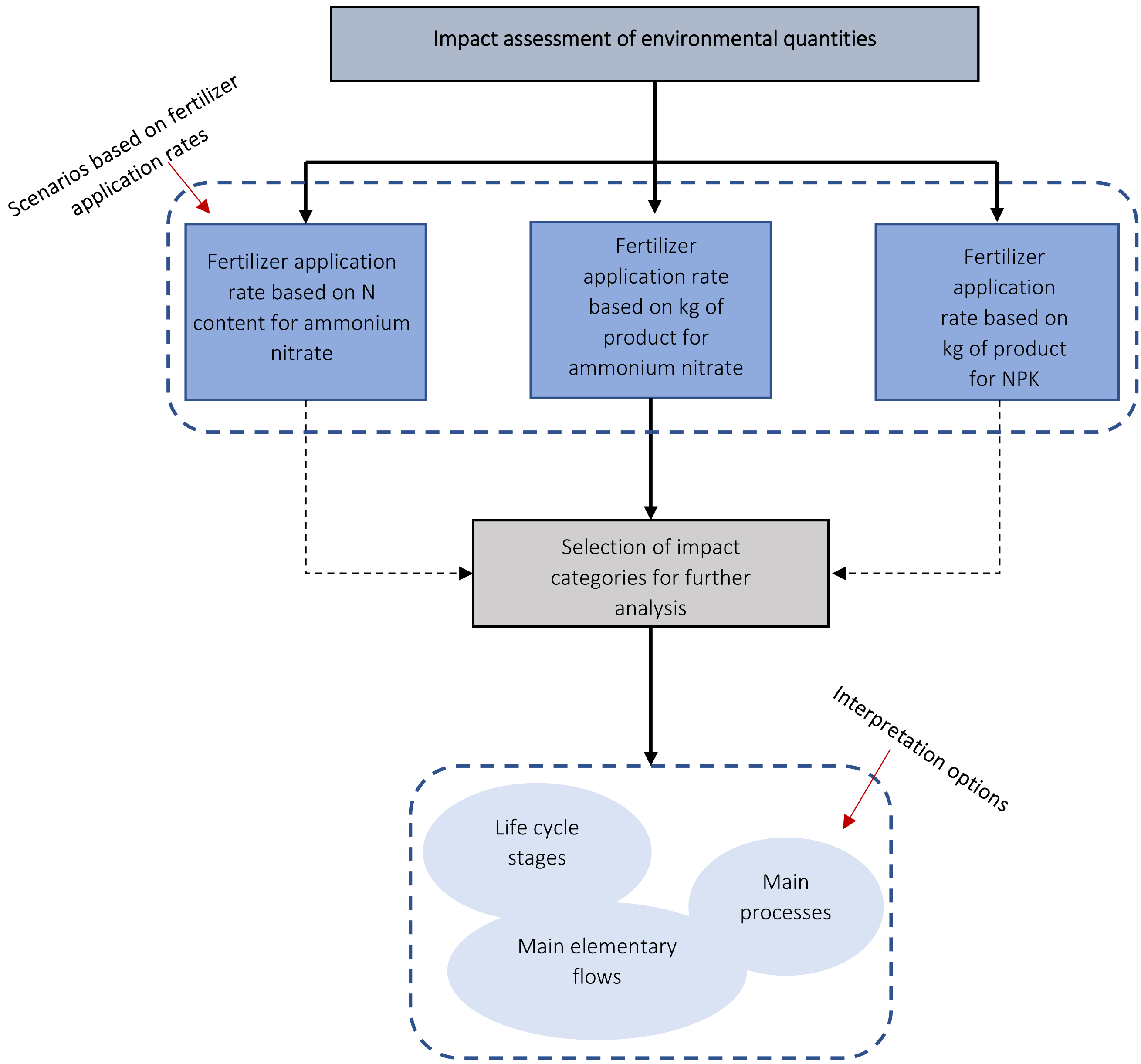

Figure 1 - Framework for selecting scenarios based on application rates impact categories and interpretation options

1. CO_2 based fertilizer is applied at a rate of nitrogen content equal to ammonium nitrate application rates. This assumes that there is a need for 200 kg of N per hectare of winter wheat crop. 200 kg of N equals 580 kg of ammonium nitrate fertilizer and 2,058 kg of CO_2 based fertilizer

2. CO_2 based fertilizer is applied at the same product rate rather than ammonium nitrate regardless of the nitrogen levels. This equals an application rate of 580 kg of product for both types of fertilizers per hectare of winter wheat crop

3. A third option considers that since the CO_2 based fertilizer is a compound fertilizer it requires less product as is the case for most NPKs. It is assumed that the application rate is the same as Yara Mila® (Yara, 2019) another compound fertilizer. The rate is set as 325 kg of product per hectare of winter wheat crop. It is understood that the CO_2 based fertilizer does not have the same NPK composition as Yara Mila® (and therefore is unlikely to emulate its performance), however the application rate is used to create a range from low - high for identifying potential emission savings

As there is no detailed field data available, by assessing three different application rates a reasonable operational range can be obtained. As the information by the stakeholder suggests that the CO_2 based fertilizer has the same performance of a commercial AN fertilizer, Option 2 has been selected as the main fertilizer application rate for the impact assessment and the interpretation. However, the range of emissions varies greatly depending on the amount of fertilizer used per hectare of crop as seen in Figure 2, where kg CO_2 eq. emitted lowers as less fertilizer is used in the field. As more field data becomes available, the inventory, LCIA and interpretation need to be adjusted to more accurate values (either through amending the existing study or commissioning a new one).

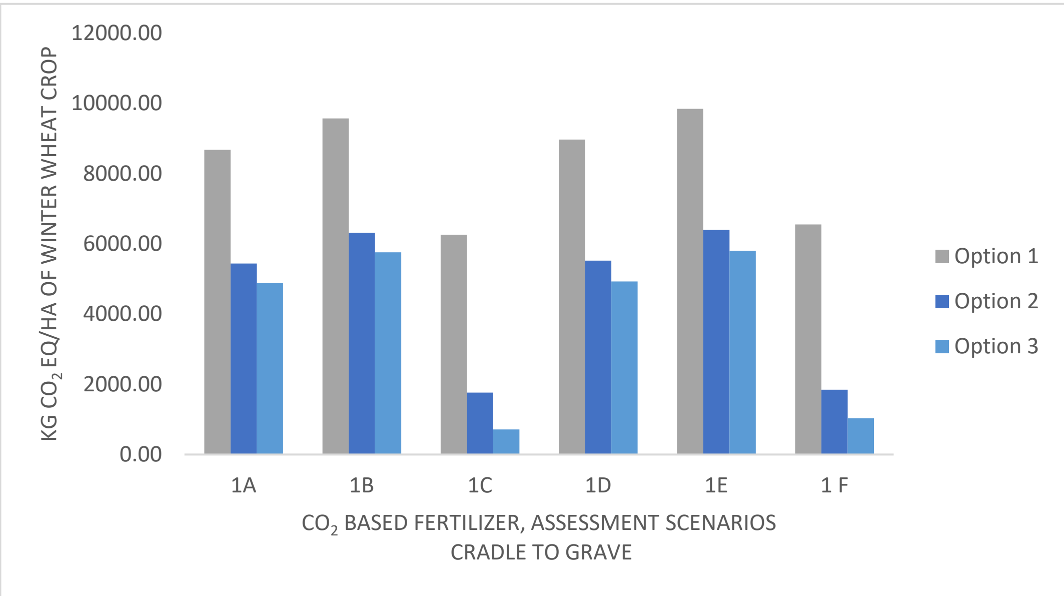

Figure 2 - kg CO_2 eq. emitted for each fertilizer application rate to field for CO_2 based fertilizers assessment scenarios

Note: The fertilizer application rates do not vary for assessment scenarios 2A to 5B as these are reference processes with a known fertilizer application rate to field.

2.1 Cradle to grave versus cradle to farm gate

Once a CO_2 based fertilizer application rate of 580 kg of product to field is chosen as the main assessment scenario, the boundaries set in "Inventories: worked example for CO_2 based fertilizer production" can be assessed and interpreted. Both cradle to gate and cradle to grave boundaries were considered from the goal and scope of the study. Since field data is in its early days, according to the guidelines, the study is fit for a preliminary study from cradle to gate. If a full study was to be made, then the boundaries would shift to cradle to grave as the CO_2 based product has a different composition than the reference products as mentioned in the guidelines. The effects on climate change for both boundary options are shown in figures 3 and 4.

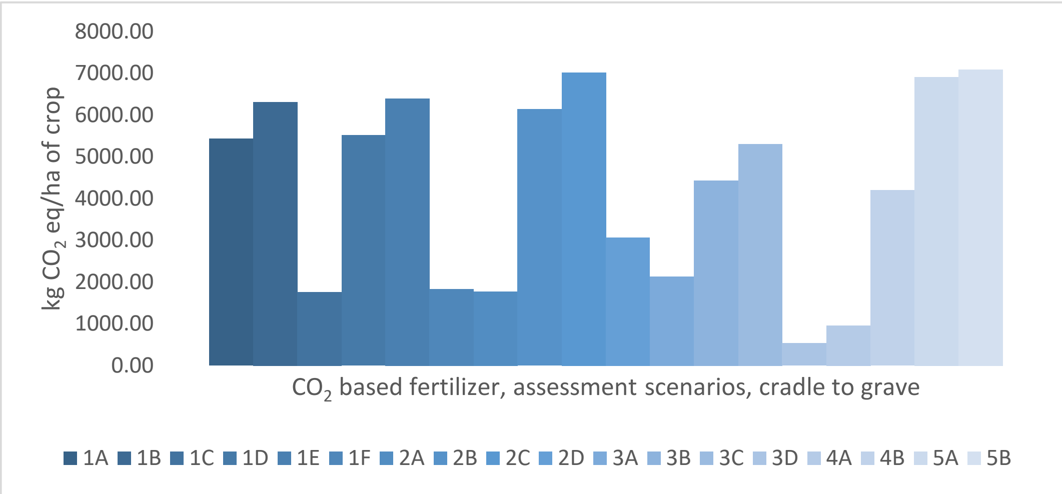

Figure 3 - kg CO_2 eq. emitted for CO_2 assessment scenarios/ha of winter wheat crop, cradle to grave boundary

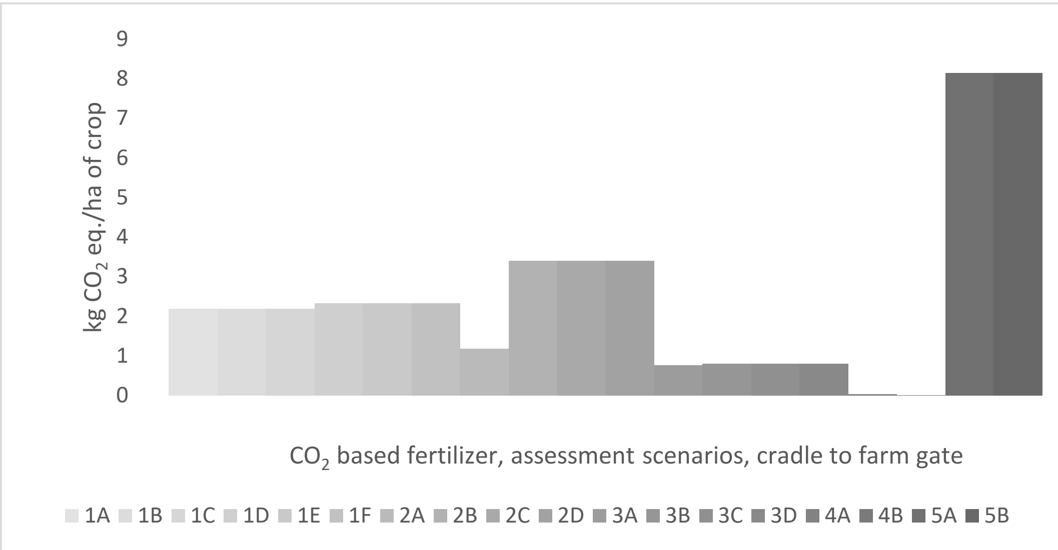

Figure 4 - kg CO_2 eq. emitted for CO_2 assessment scenarios/ha of winter wheat crop, cradle to farm gate boundary

By moving the boundaries of the study the interpretation and recommendations can vary greatly. In this worked example if a cradle to farm gate boundary is used then at first glance the CO_2 based fertilizer appears to product perform well when compared to the reference products from Ecoinvent scenarios 5A and 5B (which have full background data). Emissions (in kg CO_2 eq.) are lower by approximately 5 times on a per kg basis of product when using CO_2 based fertilizers (scenarios 1A to 1F) compared against the reference fertilizers. However, if a cradle to grave boundary is considered, then the CO_2 based fertilizer does not have the same kg CO_2 eq. savings for all assessment scenarios as when calculated on a kg basis compared to the Ecoinvent reference products. Instead, there is a variable range of emission savings from 1 to 5 times less kg CO_2 eq. when using CO_2 based fertilizers compared to Ecoinvent reference fertilizers. From figure 2 and 3 it can be seen that field application is a major contributor to total kg CO_2 eq. emissions, therefore there are limitations to only using a cradle to farm gate approach.

Note:

There is a use for cradle to farm gate boundaries in preliminary studies. Hotspot analysis is particularly useful for identifying problem areas in low TRL technologies before these are scaled to larger systems. As stated in the guidelines, having a strong goal and scope of the study will prevent confusion and misinterpretation further down the study. The limitations of the study should be clear at all times and the recommendations should be aligned to these.

2.2 Multiple inventories and their impact assessment results

In this worked example eighteen LCI variations were assessed to discuss how different approaches to collecting an LCI will affect subsequent results and outcomes in the LCA process. This lead to creating six different LCIs for CO_2 based fertilizer, four LCIs for ammonium nitrate, four LCIs for NPK fertilizers, two for organic fertilizers and two for fertilizer mixes. All LCIs have different degrees of foreground and background data (See Section 3 in Inventories: worked example for CO_2 based fertilizer production).

Above in Figure 3 and 4 the impact assessment results for climate change for each assessment scenario are shown. While it is expected for there to be an emission difference between different types of fertilizer there is also a difference between each assessment scenario for the same type of fertilizer. The range of potential emissions is significantly larger from cradle to grave than from cradle to farm gate. This is a reflection of how little field data and background information is available for this case. Figure 5 shows the sensitivity of each fertilizer type considering all scenarios under assessment, using a cradle to grave boundary for kg CO_2 eq. emissions. Fertilizers from commercial LCI databases have the least emissions variations as both scenarios have background and foreground information. The more assessment scenarios with different levels of LCI completeness, the larger the emission range for the type of fertilizer.

This comparison is only based on climate change impact category as it is the category where more information is available across all eighteen LCIs. If other impact categories are chosen, a bigger variance of calculated emissions from scenario to scenario will be shown as there is little to no information on these impacts for some of the inventories – missing data increases spread by default. This is discussed further in Section 3.1.

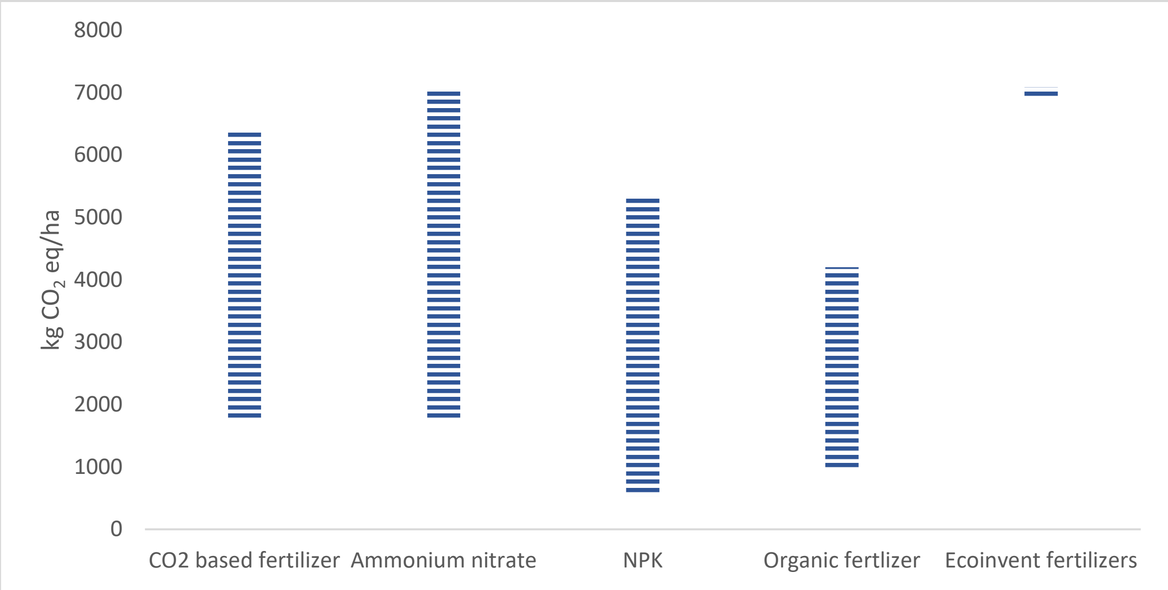

Figure 5 - kg CO_2 eq. emissions/ha winter wheat crop sensitivity of each fertilizer type considering all scenarios under assessment under cradle to grave boundary

When the same sensitivity test is performed with cradle to farm gate boundaries the range of kg CO_2 eq. emissions is narrower for several of the fertilizer types (Figure 6). This is due to the higher amount of data available for fertilizer production stage compared to the field production stage. This is true for almost all fertilizers types as companies normally will provide information on their product and rarely on the downstream processes. Having access to upstream and downstream data is one of the benefits of using commercial LCI databases. Often this data may be for a slightly different process, or different scenario thus limiting its accuracy, however this does allow for at least an approximation of a likely value. Care should be taken when using this to ensure that any conclusions drawn from using this data reflect the added uncertainty. Using these databases allows the LCA practitioner and the consumer to form an approximate idea and assess possible scenarios on the impacts of the supply chain downstream if exact, situation-specific information is not available.

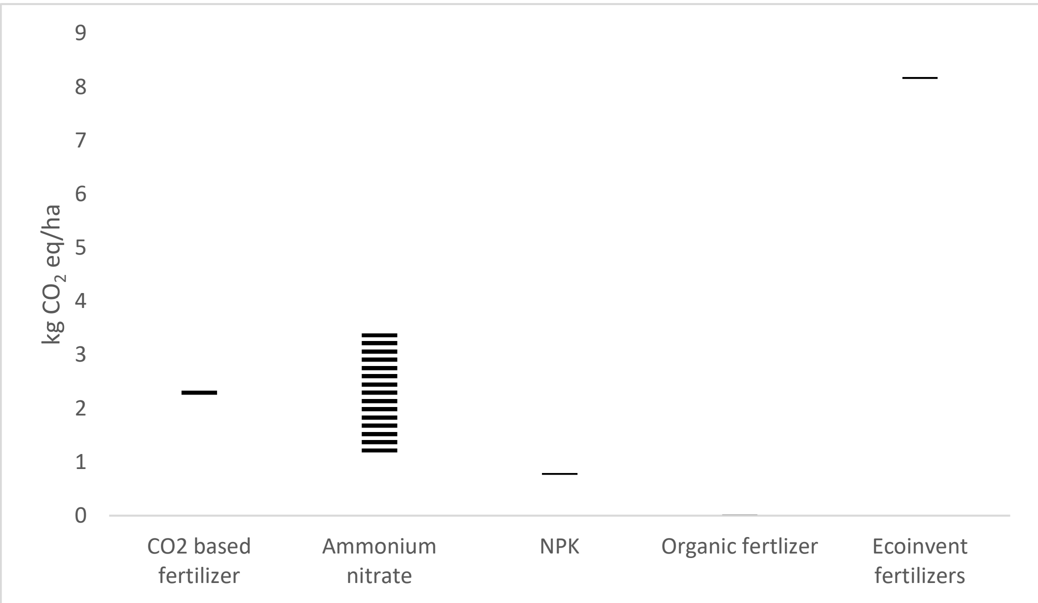

Figure 6 - kg CO_2 eq. emissions/ha winter wheat crop sensitivity of each fertilizer type considering all scenarios under assessment under cradle to farm gate boundary

For the CO_2 based fertilizer assessment scenarios, the main differences in impact assessment results are:

Cradle to grave boundary

- Assessment scenarios 1C and 1F have the lowest carbon equivalent emissions of all six LCI options. The notable difference is the use of Fertiliser Europe carbon footprint values for an NPK fertilizer which are lower than those from Ecoinvent and literature that consider higher percentages of nitrogen content in their mineral fertilizer data.

- Assessment scenarios 1B and 1E have the highest carbon equivalent emissions of all six LCI options. The notable difference is the use of Ecoinvent values for field production. Ecoinvent has full background data available, as discussed previously, for "field production" (i.e. any input that will go into the field) unlike the literature-mix assessment scenarios. The Ecoinvent database is based on mineral fertilizers with higher nitrogen content than the NPK considered by Fertilizers Europe.

Cradle to farm gate boundary

- There is a lower variance in impact results with this boundary as there are only two databases involved: the stakeholder's data and Ecoinvent impact values for anaerobic digestion. Removing the field production stages lowers the range of kg CO_2 eq. emitted per fertilizer type as it is the stage with less information available (due to the sensitivity reasons discussed previously).

For the ammonium nitrate assessment scenarios, the main differences in impact assessment results are:

Cradle to grave boundary

- Assessment scenarios 2A and 2D have the lowest emissions values as it uses Fertilizer Europe carbon footprint values which are lower than all other available databases.

Cradle to farm gate boundary

- Same conditions as cradle to grave boundary apply.

For the NPK assessment scenarios, the main differences in impact assessment results are:

Cradle to grave boundary

- There is a considerable difference between using Fertilizer Europe carbon footprint and other LCI combinations. When using Fertilizer Europe values, the emissions lower by almost ten times compared to an impact assessment using commercial data from product companies and Ecoinvent.

Cradle to farm gate boundary

- Same conditions as cradle to grave boundary apply.

For the organic fertilizer assessment scenarios, the main differences in impact assessment results are:

Cradle to grave boundary

- There is a large difference between the results from assessment scenario 4A and 4B. 4B uses a complete database from Ecoinvent, whilst 4A uses mainly one literature source as reference.

Cradle to farm gate boundary

- Same conditions as cradle to grave boundary apply.

For the fertilizer from commercial database assessment scenarios, the main differences in impact assessment results are:

Cradle to grave boundary

- There are no significant differences between the scenarios as the results from both come from using complete LCIs from Ecoinvent.

Cradle to farm gate boundary

- Same conditions as cradle to grave boundary apply.

Note:

The LCA practitioner ultimately decides which inventory is used for the assessment and the level of completeness. It is therefore a must to provide detailed data of the assumptions made along with sensitivity and uncertainty analyses to ensure that the final recommendations are useful to the consumer, stakeholder or any person-group for which the information is tailored to.

3 Interpretation

With the range of kg CO_2 eq. emitted calculated in Section 2.2 several interpretations can be made dependent on which assessment scenarios are compared between each other. To illustrate these possibilities, the following diagrams (Figure 7-9) show the interpretation options for CO_2 based fertilizer product compared against the other fertilizer types for total kg CO_2 eq. emissions. These diagrams show the sensitivity of the interpretation phase as some combinations lead to CO_2 based fertilizer having higher total kg CO_2 eq. emissions than the reference product and other combinations to have lower emissions than the reference product.

When comparing CO_2 based fertilizer against ammonium nitrate fertilizer, in 54% of the possible interpretations routes the CO_2 based fertilizer will have lower impacts on climate change (Figure 7). This makes it an uncertain result as there is about an equal chance of presenting either higher or lower emissions values as the final interpretation. There are also interpretation variations within each type of fertilizer product assessment scenario.

When comparing CO_2 based fertilizer scenarios against ammonium nitrate with an LCI from company and literature based data, there is a 66% possibility that the CO_2 based fertilizer will have lower impacts on climate change. There is an 83% possibility of CO_2 based fertilizer having higher impacts on climate change when comparing to ammonium nitrate with an LCI from Fertiliser Europe.

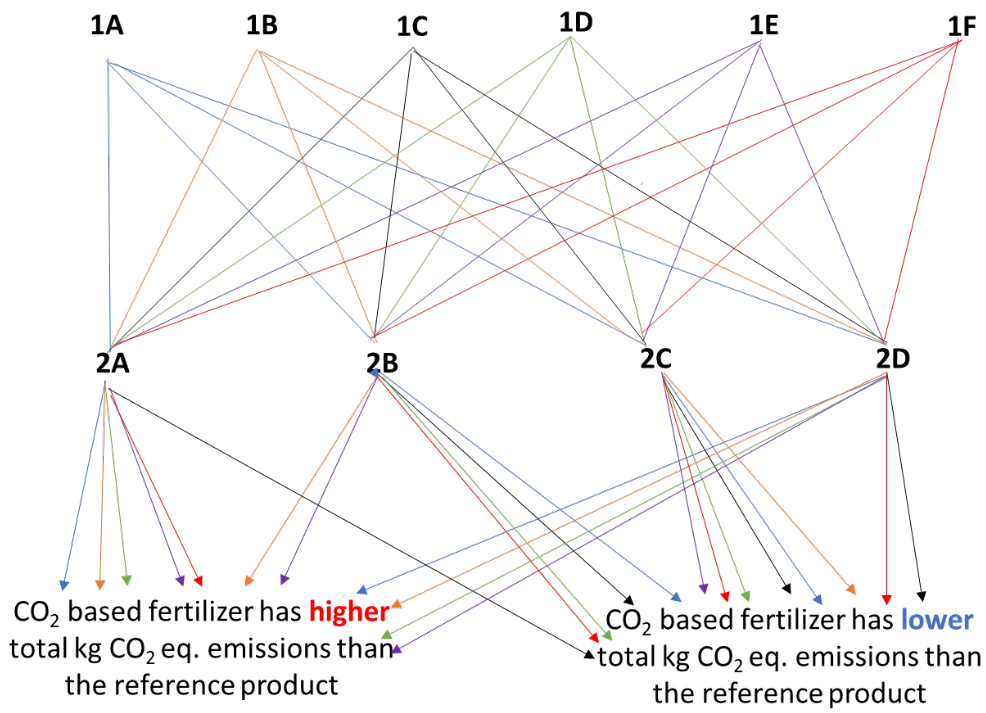

Figure 7 - CO_2 based fertilizer product compared to ammonium nitrate fertilizer assessment scenarios

For a comparison of CO_2 based fertilizer and NPK fertilizer, in approximately 80% of the possible interpretation routes the CO_2 based fertilizer will have higher impacts on climate change (Figure 8). Only assessment scenario 3D sees all CO2 options perform worse than the reference case (Fertilizer Europe for field production & company data for fertilizer production). This is due to the relatively low carbon footprint of the field production data used. All other assessment scenarios have a range of 66 to 83% where impacts on climate change are higher for CO_2 based fertilizer.

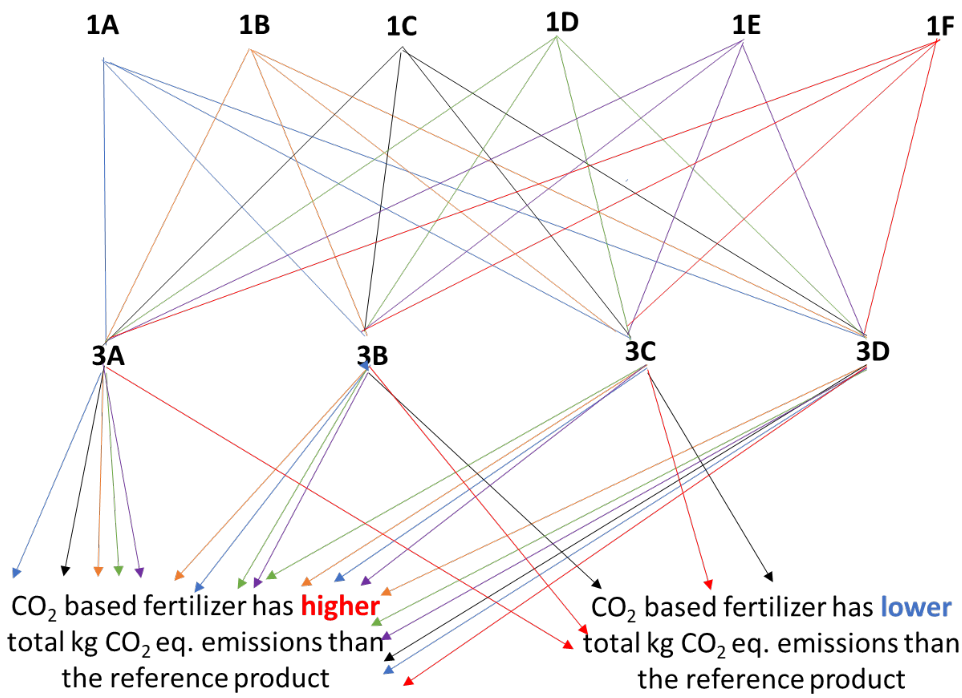

Figure 8 - CO_2 based fertilizer product compared to NPK fertilizer assessment scenarios

For CO_2 based fertilizer compared against organic and mineral fertilizer (Figure 9), 92% of the possible interpretations routes the CO_2 based fertilizer will have higher impacts on climate change for the organic fertilizer and 100% of the possible interpretations routes the CO_2 based fertilizer will have lower impacts on climate change for the mineral fertilizer (database from Ecoinvent). One of the benefits of using commercial databases for LCI such as Ecoinvent is that it will give uniform results compared to picking and mixing data as seen in these diagrams (Figure 7-9).

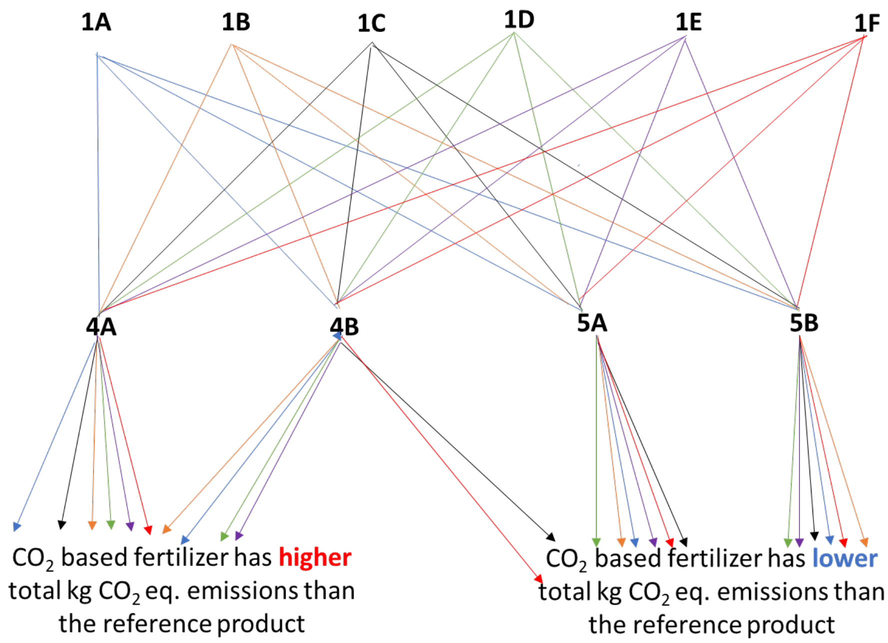

Figure 9 - CO_2 based fertilizer product compared to organic and mineral fertilizer assessment scenarios

As seen above, the interpretation stage is linked directly to the quality of the inventory, the less data available for the assessment, the more uncertain the result. For this worked example the following statements can be made with the impact assessment results:

1. There is potential for CO_2 based fertilizer to be competitive against commercial ammonium nitrate if the kg of product used in field per hectare are equal or less than ammonium nitrate usage.

2. With the fertilizer application rates tested, CO_2 based fertilizer is not competitive against commercial NPK fertilizers.

3. With the information collected for organic fertilizer, CO_2 based fertilizer is not a competitive product.

4. CO_2 based fertilizer is competitive against mineral fertilizer mixes with all application rates when commercial LCI databases are used for background data.

5. Incomplete inventories such as in assessment scenario 1C where there is no data on the anaerobic digestor will skew the results towards less CO_2 eq. emissions for CO_2 based fertilizer.

6. If background data for CO_2 based fertilizer assessment scenarios is completed with an LCI from commercial database (e.g. assessment scenario 1E), CO_2 based fertilizer product will have higher kg CO_2 eq. emissions in 75% of all the assessment scenarios. However, it will have 100% less kg CO_2 eq. emissions when compared to reference products that also use commercial LCI databases.

Note:

The assessment scenarios used in this worked example are a way to test the sensitivity of the life cycle inventory stage. It is understood that creating multiple life cycle inventories for each study and assessing them is not always feasible. However, through this worked example it is shown that although the way that impacts are assessed does not change regardless of the data involved, erroneous interpretation of those results can easily occur. As suggested by the guidelines, if results and/or gathered data quality is not sufficient, either the model shall be refined or the goal and scope shall be adapted. This scenario analysis shows the benefits of using full background data from commercial databases against only literature values or limited information by the stakeholder. It is suggested to use these commercial databases whenever possible as a starting point and the use of these is particularly useful for low TRL technologies as it is often the case for CO_2 utilization processes.

3.1 Interpretation of other impact categories

Up until this point, the interpretation stage has solely focused on climate change. For the environmental study to be classified as a “full” LCA, then other impact categories also have to be considered. Once the impact assessment results are obtained then a selection of categories for further analysis can be made. As seen with climate change results, the quality of the LCI will determine the usefulness of the study as a whole, this is also applicable for all other impact categories. Table 2 shows how many of the assessment scenarios for each fertilizer type will show a result in all impact categories in percentages for cradle to grave boundaries for 1 ha of winter crop for all fertilizer types and using 580 kg of CO_2 based fertilizer for field application.

Table 2 - Percentage of assessment scenarios with results in all impact categories for each type of fertilizer (cradle to grave)

Fertilizer types	Assessment scenarios with a result in all impact categories (%)
CO_2 based	100
Ammonium nitrate	50
NPK	50
Organic	100
Mineral	100

If only Table 2 is considered, then CO_2 based fertilizer can be compared against organic and mineral fertilizers (which have an LCI based on Ecoinvent) but not against ammonium nitrate and NPK fertilizers (which have an LCI based on company data) for other impact categories. However, there are three process stages per assessment scenario and each stage can have a different quality and quantity of information as part of the full LCI. As seen in Table 3, CO_2 based fertilizer has both missing and incomplete data for all six assessment scenarios and if looking further down the list, in 94% of the assessment scenarios there is missing or/and incomplete data for other impact categories. There are only two assessment scenarios (4B and 5B) with sufficient environmental impact results from the list of eighteen, the LCIs for these scenarios were 100 % obtained from Ecoinvent.

Table 3 - Data missing or incomplete for the LCI of each assessment scenario considering all three process stages: anaerobic digestion, fertilizer production and field production (cradle to grave)

Assessment scenarios		Missing LCI	Incomplete LCI
CO_2 based fertilizer	1A	Anaerobic digestion	Fertilizer production, field production
	1B	Anaerobic digestion	Fertilizer production
	1C	Anaerobic digestion	Fertilizer production
	1D	N/A	Fertilizer production, field production
	1E	N/A	Fertilizer production
	1F	N/A	Fertilizer production
Ammonium nitrate fertilizer	2A	N/A	Fertilizer production, field production
	2B	N/A	Fertilizer production, field production
	2C	N/A	Fertilizer production
	2D	N/A	Fertilizer production, field production
NPK fertilizer	3A	N/A	Fertilizer production, field production
	3B	N/A	Fertilizer production, field production
	3C	N/A	Fertilizer production
	3D	N/A	Fertilizer production, field production
Organic and mineral fertilizer	4A	N/A	Fertilizer production, field production
	4B	N/A	N/A
	5A	N/A	Field production
	5B	N/A	N/A

Considering the lack of a complete LCI for other impact categories, any final interpretation of results would not be accurate. At this point the goal of the study is revised and changed if needed. In this worked example one of the goals is set to compare whether there are environmental benefits between using a nitrogen based fertilizer produced from recovered CO_2 and using fertilizer production routes derived from fossil carbon sources. As there are no further specifications as to which impact categories should be considered, the goal is not changed.

However, the limitations of the study for other impact categories is well documented throughout this report – such practices should also be followed in studies that intend to follow the guidelines.

Although a full comparison for each impact category is not possible with the impact assessment results, it can still be useful to have specific results for parts of the process, particularly for hot spot analysis. In this worked example the stakeholder can still identify the contribution percentage for each scenario for all environmental quantities as it highlights environmental issues/benefits that need addressing beyond climate change. Table 4, copied directly from Inventories: worked example for CO_2 based fertilizer production, section 4.1.2, shows the contribution percent for each assessment scenario for all impact categories under CML method for CO_2 based fertilizer production. The results show that assessment scenarios 1B and 1E have higher impact contributions than other scenarios, due to both scenarios having full background data for field production from Ecoinvent.

Table 4 - Impact contributions of environmental quantities for each assessment scenario using the CML method. 580 kg of fertilizer per ha of winter wheat crop for ammonium nitrate and CO_2 based fertilizer (cradle to grave)

ENVIRONNMENTAL QUANTITIES	CONTRIBUTION (%) FOR EACH SCENARIO						
	1A	1B	1C	1D	1E	1F	Total
ADP elements	20	24	6	20	24	6	100
ADP fossil	19	24	6	19	25	6	100
AP	13	33	4	14	33	4	100
EP	9	37	3	9	37	3	100
FAETP inf.	16	31	3	16	31	3	100
GWP 100 years	30	27	-5	29	25	-6	100
GWP 100 years, excl biogenic carbon	20	23	6	20	23	7	100
HTP inf.	17	26	5	17	26	9	100
MAETP inf.	21	24	5	21	25	5	100
ODP, steady state	18	24	7	18	25	7	100
POCP	18	27	3	19	28	4	100
TETP inf.	4	45	1	4	45	1	100

When conducting further analysis on both 1B and 1E assessment scenarios, the stakeholder's production process ranges from high to medium in total impact contributions for each environmental quantity (**Figure 10**). For example, for abiotic depletion both assessment scenarios scored a high value in impact contributions for fertilizer production in respect to all other inputs. However, this does not necessarily mean that the contribution is significant to total environmental impact as it is only a comparison between inputs and not against environmental quantities. In this particular case, abiotic depletion for fertilizer production in assessment scenario 1B, the value only contributes 3% of the total environmental impact.

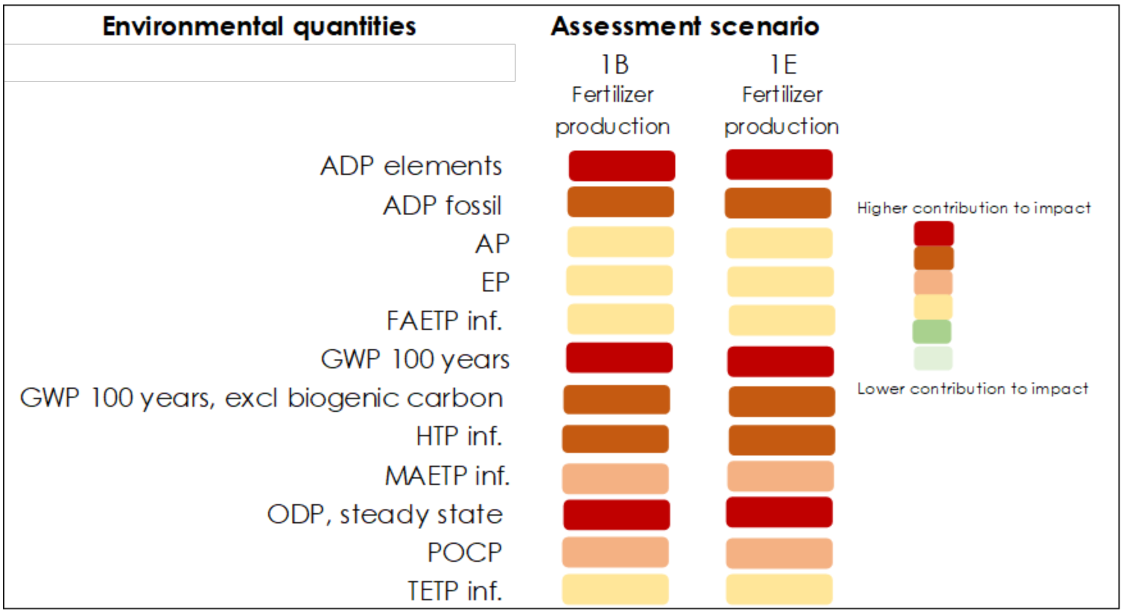

Figure 10 - Color scale for impact contributions to each environmental quantity for fertilizer production in assessment scenarios 1B and 1E (CO_2 based fertilizer, cradle to grave)

There is no significant difference in results between fertilizer production from assessment scenario 1B and 1E, thus the colour scale shown in Figure 10 is the same for both in all environmental quantities. A more in depth analysis can be carried out to determine what are the major inputs that contribute to higher environmental impacts for CO_2 based fertilizer. Using assessment scenario 1B, the results show that the input with highest environmental impact for all categories under CML method is calcium nitrate use, seconded by ammonia use for fertilizer production.

As more data becomes available, the impact assessment results can be calculated as many times as necessary to obtain more detailed environmental information that will in turn increase the robustness of the interpretation phase and the study as a whole. This can include an interpretation based on life cycle stages, processes and elementary flows as is the case for climate change in this study. For this worked example the following statements can be made of the impact assessment results for other impact categories:

1. With the current LCI, comparing CO_2 based fertilizer production to the reference processes will not give accurate values for other impact categories as there is missing and/or incomplete data for most process stages.

2. A preliminary hot spot analysis can be made for CO_2 based fertilizer production for the stakeholder to review and determine whether any changes to the process can be made or are needed.

3. The contribution analysis shows that for all six assessment scenario options for the CO_2 based fertilizer, scenarios 1B and 1E (which have background data from Ecoinvent) have the highest environmental impacts.

4. Calcium nitrate and ammonia inputs are the top environmental impact contributors in CO_2 based fertilizer production for all environmental quantities when using the current LCI. Further information can be obtained from the impact assessment results for interpretation, however it should not be used for comparative studies.

3.2 Interpretation based on life cycle stages

The LCIA includes results based on life cycle stages, processes and elementary flows. This follows the methods shown in the technical report by the JRC (Zampori L., 2016). The guidelines do not limit the method for the interpretation as there are many, however they do emphasize that the recommendations made are subjective to the interpretation undertaken. The JRC method was chosen for this example as it a straight-forward way to show environmental impacts throughout the supply chain. The interpretation undertaken is only based on climate change impacts (See section 3.1 for more information on other impact categories).

Figure 11 shows the average result for emission contributions for each type of fertilizer in percentages. This includes all assessment scenarios for all fertilizer types, the un-aggregated results can be seen in Inventories: worked example for CO_2 based fertilizer production, section 4. The averaged result indicates that for all types of fertilizers, the life cycle stage with the highest kg CO_2 eq. emitted is the use stage (approx. contribution of 60 % to 90% of total), falling in line with the general results of the study. The use stage relies heavily on full LCI data from Ecoinvent, compared to the raw material and acquisition and pre-processing stage where for commercial products there is little informative available to the public and emissions are all assigned to the production of the main product. At the time of writing this report, there were no direct GHG emissions reported from producing CO_2 based fertilizer and all kg CO_2 eq. emissions were assigned to raw material acquisition and pre-processing (also known as scope 2 emissions).

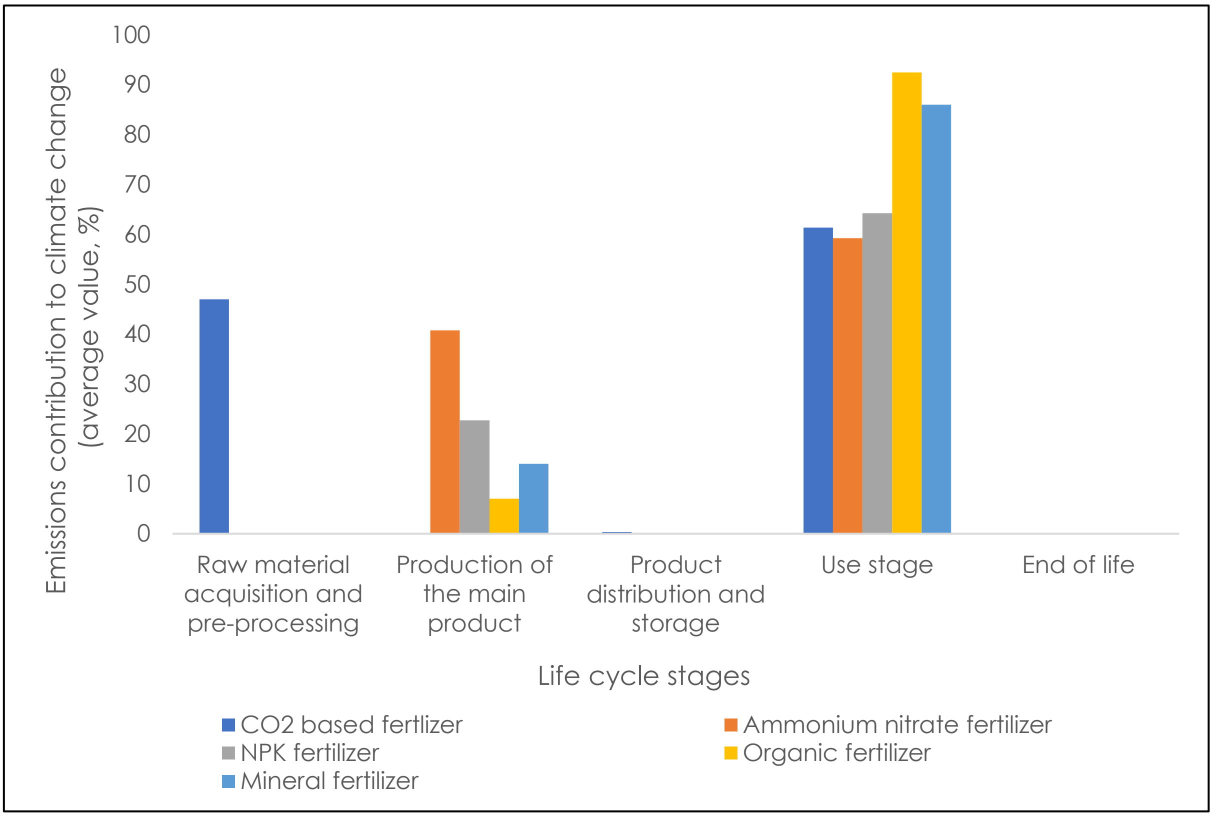

Figure 11 - Impacts to climate change divided in life cycle stages for the production of 1 ha of winter wheat crop (cradle to grave). Averaged values for assessment scenarios 1A to 1F

For this worked example the following statements can be made of the impact assessment results to climate change based on life cycle stages:

1. The use stage has in average the highest percentage of kg CO_2 eq. emitted across the supply chain of all fertilizer types and all assessment scenarios.

2. There is limited information on end of life and product distribution and storage for most fertilizer types and assessment scenarios and should be taken into consideration before providing recommendations.

3. Only CO_2 based fertilizer has raw material acquisition and pre-processing emissions assigned to it, as other fertilizer types have aggregated LCIs.

4. Further breakdown of the results can be carried out if needed, the results show that GHG emissions are largely in two clusters: use stage and production of the main product.

Note:

Showing results on a life cycle stage basis can also be useful for preliminary studies where the boundaries are only cradle to gate such as it is the case for many CO_2 utilization processes and it is another way of identifying hot spots.

3.3 Interpretation based on processes

An interpretation based on processes can be made to obtain further information on the environmental impact of the CO_2 based fertilizer on climate change. The EIA is shown in Inventories: worked example for CO_2 based fertilizer production, section 4. If more detailed information for the reference product is available, a comparison between processes can be made. However, a CO_2 utilization product will not have the same production process as the reference product, thus as basis a comparison between total impact values should be considered first.

Figure 12 shows the seven process that account for 80 % to 90% of total kg of CO_2 eq. emitted for the use of 580 kg of fertilizer per ha of winter wheat crop. Amongst these, wheat production on average is responsible for 45% of the total kg of CO_2 eq. emitted for all assessment scenarios for CO_2 based fertilizer production. Irrigation to field and calcium ammonium nitrate are also emission hotspots for most assessment scenarios.

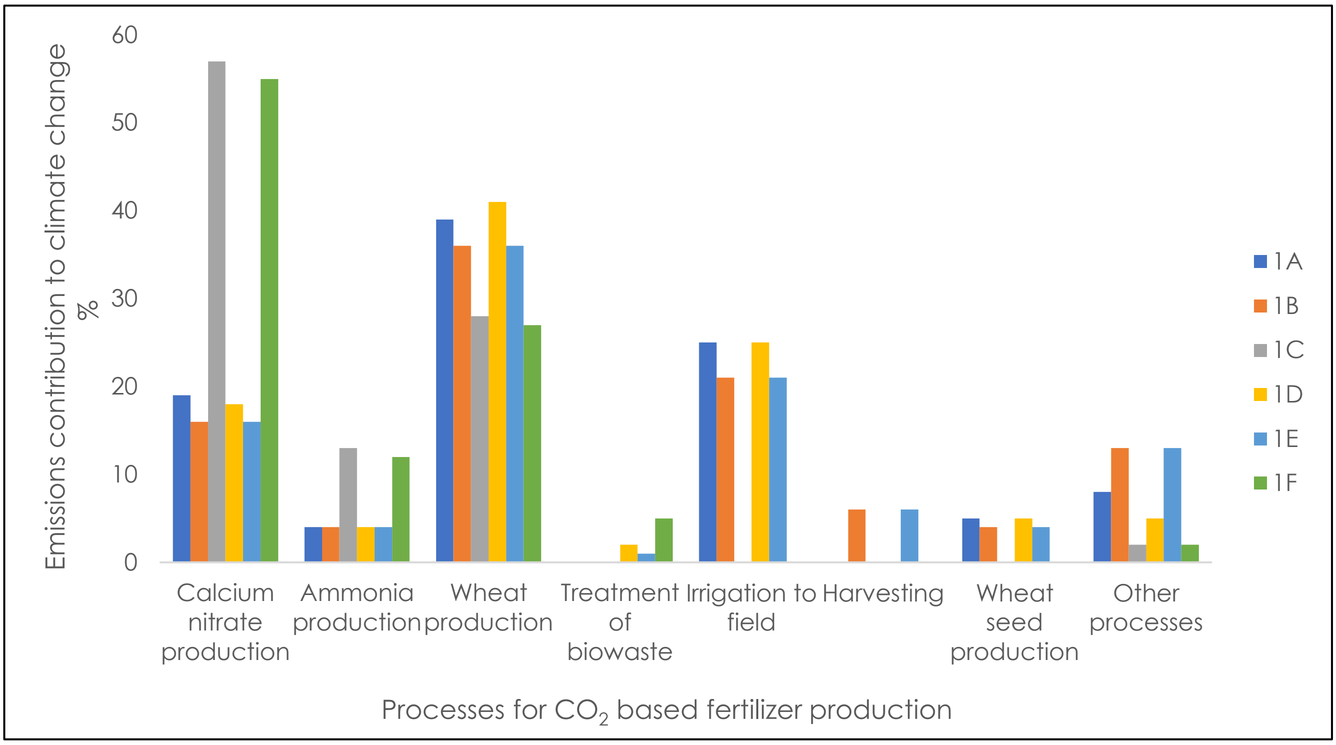

Figure 12 - Impact to climate change in percentages for CO_2 based fertilizer production processes (scaled to 580 kg of fertilizer for 1 ha of winter wheat crop, cradle to grave)

The key points from using results for processes in this worked example are:

1. The cut-off point to ensure that all relevant environmental impacts are accounted for was set at 80 %. This percentage is covered by approximately 5 main processes: Wheat production, calcium nitrate production, irrigation to field and wheat seed production. However, the results have been expanded to include 7 processes with account for 87 to 98 % of known impacts for all CO_2 based fertilizer assessment scenarios.

2. Calcium nitrate production has higher kg CO_2 eq. emissions for assessment scenarios 1C and 1F as it does not have the same high level of data for field production as other scenarios. These two values skew the LCIA results for calcium nitrate production in favor of higher emissions. Regardless of these two values, calcium nitrate production is still considered a hot spot process for calcium nitrate production.

3. For the stakeholder, calcium ammonium nitrate and ammonia production are the top two GHG emitters with cradle to gate boundaries.

4. Irrigation to field is also a top contributor to GHG emissions, this is not reflected in assessment scenarios 1C and 1F as the carbon footprint used from Fertilizer Europe for field production is an absolute value.

Note:

The benefits of having scenario analysis or multiple LCI scenarios is shown throughout this report. By having a range of results it is possible to obtain a wider picture of the outcome of the LCA which can help with final recommendations. As mentioned before, it is well known that time and budget constraints can limit the scope of

data gathering, thus relying on already completed and full LCA is highly recommended as well as the use of standardized scenarios whenever possible (see Section 3.5).

3.4 Interpretation based on elementary flows

Further details on the environmental impact to climate change can be obtained from elementary flows to and from the CO_2 based fertilizer production system (cradle to grave). The full EIA results are shown in Inventories: worked example for CO_2 based fertilizer production, section 4. The flows considered for this assessment include: emissions to air, fresh water, sea water, agricultural soil and industrial soil. It also considers the GHG emissions from the seven processes highlighted as top emitters. From this it is possible to identify which are the elementary flows that have higher impacts to climate change for each process of each assessment scenario (1A to 1F). The results are also shown in percentages as this is an effective way to show how much does a process/flow contributes to the environmental burden of the whole process in respect to the other processes/flows and it is also an option to protect sensitive company data through normalization. The summary of these results are in Table 5 where the processes that impact the most an elementary flow in terms of climate change impacts are shown.

Table 5 - Top processes that contribute to higher impacts to climate change for each main environmental flow (cradle to grave)

Flows	Processes that contribute to higher impacts to climate change
Emissions to air	Wheat production and irrigation to field
Emissions to fresh water	Irrigation to field
Emission to sea water	Calcium nitrate production
Emissions to agricultural soil	All other processes, wheat production
Emissions to industrial soil	All other processes, wheat production

The key points from using results for elementary flows in this worked example are:

1. Because this assessment only includes climate change impacts, emissions to agricultural soil and emissions to industrial soil have higher uncertainty. With approximately 30% of unknown emissions, this is a higher percentage than the cut-off goal of 80 % of documented emissions allows. Emissions to air, fresh water and sea water fall within the 80 % known emissions cut off. This highlights the limits of conducting a full LCA study when there is not sufficient data for other impact categories. With the information provided in Section 3.1 a preliminary assessment for all other impact categories can be made for hotspot analysis without using it for comparative studies and with the understanding of the limitations of the study.

2. Emissions to air and emissions to industrial soil have calcium nitrate production as the highest GHG emitter for assessment scenarios 1C and 1F. This is in line with previous results and suggests that those two scenarios work best under cradle to gate condition as they do not have sufficiently robust LCIs for a cradle to grave assessments.

3. In general, wheat production and irrigation to field are the two processes that contribute the most GHG emissions to all environmental flows.

Note:

As mentioned throughout this worked example, there is no "one way fits" all for interpretation. It is however useful to focus on how to communicate the findings in a clear and concise way, particularly for the benefit of the non LCA experts who can get overwhelmed easily with the heavy load of data given in one study.

3.5 Standardized scenarios

The guidelines include standardized LCIA scenarios for hydrogen, CO_2 supply, heat supply, natural gas and electricity. The aim of these scenarios is to help to avoid scenario generation for each LCA study and to allow comparison between technologies when this is not possible due to non-harmonized inputs. Whilst many CO_2 utilization technologies rely on external hydrogen and CO_2 sources, the CO_2 based fertilizer studied here is produced from an integrated process that requires small amounts of extra energy but large amounts of other inputs such as calcium ammonium nitrate and ammonia. Table 6 shows the standardized results for CO_2 based fertilizer production (assessment scenario 1A, cradle to gate) as an example of applying the standardized scenarios to electricity input.

The electricity required for the production of fertilizer is mostly for auxiliary processes such as mixing, pumping etc. From the current values to a full decarbonized electricity scenario there is a reduction of 1 to 2 % of the total impact assessment results for all category with the exception being abiotic depletion for elements. There is an increase of 0.3 % in the LCIA results for ADP elements and can be linked to the use of turbines for wind power, which have high material inputs. Using the full decarbonized electricity scenario for climate change, a 1 % of total GHG emission can be saved. This is not enough to alter any of the comparisons made throughout this work and the interpretation remains the same. With the data collected there is not sufficient unaggregated information from the reference process to also apply decarbonized scenarios. It is unlikely that electricity inputs in any assessment scenario would swing the results towards the other end as electricity impacts are not amongst the highest for fertilizer production.

Note:

Although the standardized scenarios do not show many changes to the results for this particular worked example, this is not the case for many CO_2 utilization processes that rely heavily on renewable energy and separate CCS systems. It is good practice to include these scenarios as they can be useful for other practitioners if comparisons are needed.

Table 6 Life cycle impact assessment results for standardized scenarios applied to assessment scenario 1A cradle to grave

Environmental quantities	Without standardization	Status quo	Low decarbonized	High decarbonized	Full decarbonized
CML2001 - Jan. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	0.00535	0.005354	0.005362	0.005365	0.005365
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	11200	11190.83000	11101.19000	11069.87000	11054.31800
CML2001 - Jan. 2016, Acidification Potential (AP) [kg SO2 eq.]	5.67	5.64	5.62	5.62	5.61
CML2001 - Jan. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	4.59	4.58	4.58	4.58	4.58
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	185	182	182	182	182
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	1270	1270	1261	1258	1257
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	1270	1270	1261	1259	1257
CML2001 - Jan. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	644	641	641	641	641
CML2001 - Jan. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	681000	666752	667184	667400	665306
CML2001 - Jan. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	0.000103	0.00010	0.00010	0.00010	0.00010
CML2001 - Jan. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	0.257	0.256	0.254	0.254	0.254
CML2001 - Jan. 2016, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	11.70	11.69	11.69	11.69	11.68

4. Limitations

The main limitations to take into consideration when interpreting the results have been mentioned throughout the report, in summary:

1. It is a worked example to show the application of the guidelines to the interpretation phase of an LCA. Results should not be used for any other purposes and are only illustrative

2. The LCI for the CO_2 based fertilizer production is limited to that provided by the stakeholder. There was no data collected on site

3. Carbon footprints for reference products were obtained directly from company websites with not further involvement from company. This limits the comparison between processes to only climate change impacts as there is not sufficient data for other impact categories

4. The stakeholder has limited data on field production, commercial databases have been used to complete background data

5. Anaerobic digestion is not provided by the stakeholder in detail, a commercial database has been used as a generic model for assessment scenarios 1D to 1E

6. No Monte Carlo analysis is performed as important variables in the foreground system cannot be varied in the background system

7. The assumption that CO_2 based fertilizer is spread in the same quantities to field based on kg of product as ammonium nitrate has been made. The LCIA results have been used for the interpretation section. As more detailed field data is collected, the results should be calculated and interpreted as many times as necessary

5. Conclusions

The aim of this worked example was to focus on the interpretation phase highlighting points where misinterpretation can arise from common LCA pitfalls and errors: missing data, using alternative scenarios, shifting boundaries and so on. This is of relevance to LCA practitioners, stakeholders and policy makers who use the interpretation to obtain environmental recommendations on products and processes. The worked example uses data provided by the stakeholder on the production of a CO_2 based fertilizer from digestate sludge. The data used to create a life cycle inventory lead to producing eighteen different inventories all with different degrees of data quality. By having several inventories for one same study (called "assessment scenarios" in this work) issues with "cherry picking" data were identified in the interpretation phase. In this worked example the impacts assessment results can lead to the following interpretation statements depending on the combination of data used for the assessment:

1. CO_2 based fertilizer production has higher GHG emissions compared to ammonium nitrate fertilizers in 56 % of the possible interpretations, 80 % for NPK fertilizers and 92 % for organic fertilizers (cattle manure) and 0 % for mineral fertilizers (taken from Ecoinvent).

2. CO_2 based fertilizer production has lower GHG emissions compared to ammonium nitrate fertilizer in 44 % of the possible interpretations, 20 % for NPK fertilizers, 8 % for organic fertilizers and 100 % for mineral fertilizers (taken from Ecoinvent)

Furthermore, there is also interpretation variations within each type of fertilizer product assessment scenario, widening the range of possible conclusions from the assessment. This highlights the need for uniform data when creating LCIs and the theory behind this is discussed throughout the guidelines. In practice it is easy to miscalculate the level of accuracy of data collected even if primary sources are used. This is in particularly true for CO_2 utilization processes where TRL are often low limiting both foreground and background data collection. The amount of data relevant to a process can be overwhelming, especially if none of it "fits" 100% with the product under assessment (also common with CO_2 utilization technologies). The results of "Picking and mixing" data for an LCI that is then assessed and interpreted is shown and discussed in this work. Based on the results from this work, the following conclusions were made:

- Assessment scenarios with commercial databases were proven to be the least sensitive to change out of all the LCI combinations. It is suggested to use commercial databases to obtain background data whenever possible as a starting point for conservative results. If commercial databases are not available and primary data is limited, the goal and scope should be modified accordingly

- "Picking and mixing" data has a higher impact on the assessment of other environmental quantities (abiotic depletion, human toxicity, etc) than for climate change in this worked example. This is due to lack of uniformity in the datasets which leads to filling the inventory gaps with data from various sources, thus higher rates of "picking and mixing" are achieved leading to potential inconsistencies

- The use of standardized scenarios such as the ones presented in the guidelines, are particularly useful for other impact categories which are usually more limited by data constraints than for impacts associated to climate change

- Hotspot analysis is useful for this worked example as it allows the stakeholder to see the pitfalls or benefits of the process even when there is limited information downstream of the process

- Shifting boundaries from "cradle to grave" to "cradle to farm gate" can lead to different interpretations. In a cradle to farm gate approach there are less GHG emissions per functional unit than when the boundaries shift to cradle to grave. Care should be taken when using the cradle to farm gate approach even for preliminary studies. As suggested in the guidelines, CO_2 based fertilizer is considered a CO_2 based chemical and the basis for comparison should be on technical performance with cradle to grave boundaries when doing full studies

- For the specific results of the worked example that answer to the goal: there is a potential for CO_2 based fertilizer to be competitive in terms of climate change impacts against commercial ammonium nitrate if the kg of product used in field per hectare are equal or less than ammonium nitrate usage, however with the same application rates it is not competitive against commercial NPK fertilizer and organic fertilizer. CO_2 based fertilizer is competitive against mineral fertilizer mixes with all application rates when commercial LCI databases are used for background data

- Calcium nitrate and ammonia inputs are the top environmental impact contributors in CO_2 based fertilizer production for all environmental quantities

- The use stage has on average the highest percentage of kg CO_2 eq. emitted across the supply chain of all fertilizer types and all assessment scenarios

- Wheat production and irrigation to field are the two processes that contribute the most GHG emissions to all environmental flows for CO_2 based fertilizer assessment scenarios

- Multiple life cycle inventories are used in this worked example as a form of testing uncertainty and sensitivity and is applied to reflect the changes that the background system has on the CO_2 utilization technologies

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