Carbon Footprint Assessment of spring wheat and oat production and potential effects of emission reducing measures

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Summary

Felleskjøpet commissioned a carbon footprint analysis of the current production of spring wheat and oats used in the value chain of bread, based on statistics and literature data and is a theoretical average of Norwegian spring wheat and oat production.

The analysis also included a theoretical scenario where greenhouse gas emission reduction measures on the farm level were implemented aiming to reduce the carbon footprint. The Norwegian Institute of Bioeconomy Research (NIBIO) quantified emission reduction measures at the farm level, and NORSUS used this data in the analysis to estimate possible reduction potentials in the carbon footprint.

The baseline carbon footprint was assessed 0.60 kg CO_2e/kg for spring wheat and 0.62 kg CO_2e/kg for oats. These values are in the same range or lower than previously reported Norwegian studies mainly because our study excluded emissions from machinery, buildings, and soil organic carbon changes. Despite the narrower boundaries, the results fall within the range reported for some European countries.

Individual mitigation measures theoretically reduced the carbon footprint to varying extents, from a minor reduction of between 0.2%- 4% such as precision spreading and split fertilization. Soil compaction reduction had a moderate effect of between 4-17% reduction in the carbon footprint. The use of low-carbon fertilizer gave a substantial reduction of 20–20.5%. The total combined effect of the measures was a reduction potential of up to 26% without considering potential yield increases and up to 36% taking yield increase into account. None of the estimates considered possible interactions between the measures.

A sensitivity analysis was performed to assess the effect of yield reduction and removal of straw from the field. Yield reductions increased per-kg emissions by ~17%, demonstrating that yield stability is crucial for maintaining low carbon footprints. The effect of straw management indicated that not removing straw may reduce greenhouse gas emissions by 0.3-0.6%.

In conclusion, this study indicates that carbon footprint reductions in Norwegian cereal production are achievable. It is however important to note that limitations of the study imply that the results should be interpreted as indicative estimates of relative performance and potential improvement, rather than precise absolute values.

Contents

1 Introduction

Felleskjøpet commissioned the Norwegian Institute for Sustainability Research (NORSUS) to perform a life cycle assessment (LCA) of the carbon footprint of a product (CFP) associated with the Norwegian production of spring wheat and oat primarily intended for bread production. Although the analysis is framed around the bread value chain, the primary production stages assessed are representative of oats and wheat that may also be allocated to other value chains. The assessment aimed to establish a representative baseline for Norwegian production and to estimate the potential effects of selected greenhouse gas (GHG) mitigation measures implemented at the farm level.

The baseline scenario represents a theoretical average of current Norwegian spring wheat and oat production, based on statistics and literature data. Emission reduction measures were quantified by the Norwegian Institute of Bioeconomy Research (NIBIO), while Yara supplied data for a low-carbon fertilizer. These data were incorporated by NORSUS into the LCA model to estimate the potential reductions in carbon footprint per kilogram of grain produced.

The results are intended to support sustainability communication by Felleskjøpet to consumers and stakeholders, and to contribute to sustainability reporting. The intended application is defined with reference to the bread value chain; however, the quantified CFP reflects primary agricultural production and is therefore applicable to other downstream food and non-food value chains supplied by the same production system. Hence, the study can be seen as a partial carbon footprint study. The measures analyzed are currently being implemented on commercial farms contracted to Felleskjøpet, and their actual effects will be assessed at a later stage. The results from this study thus only represent a theoretical reduction potential of the carbon footprint.

The study applies an attributional LCA approach following ISO 14067, with a cradle-to-storage gate system boundary. The functional unit is 1 kg of grain (15% moisture content).

2 Goal and Scope definition

This chapter describes the purpose of the study, the products studied, the functional unit, the system boundaries, and the methodological choices made in connection with modelling.

2.1 Goal and Scope

The goal of this life cycle assessment (LCA) is to quantify the carbon footprint of a product (CFP) associated with the production of spring wheat and oat in Norway. While bread production is used as the primary reference application, the assessed production system represents primary agricultural production that may supply multiple downstream value chains. The assessment compares CFPs before and after the implementation of selected greenhouse gas (GHG) mitigation measures at the farm level. The aim is to assess the theoretical potential for reducing the carbon footprint of spring wheat and oat production, using Norwegian average production as the baseline. The on-farm measures are being implemented on real farms contracted to Felleskjøpet in different locations in Norway, and the real effect will be assessed at the end of 2025. The Norwegian Institute of Bioeconomy Research (NIBIO) quantified emission-reducing measures at the farm level and Yara supplied data for their low-carbon fertilizer, which was one GHG-reducing measure in this study. NORSUS incorporated this data into the LCA analysis to estimate potential reductions in carbon footprint.

The results will be used for sustainability communication to customers, consumers, and in sustainability reporting.

2.2 Commissioner

Felleskjøpet is the client of the study, and NORSUS – Norwegian Institute for Sustainable Research performed the study. All essential assumptions in the analysis have been decided in consultation with representatives from Felleskjøpet. The assignment was carried out during the period June-July 2025.

2.3 The studied system

This section describes the system studied and the data sources used in the study. A more detailed description of the data can be found in the section on data inventory.

2.3.1 Spring Wheat and oats

Wheat is the most important food grain grown in Norway. Wheat's good baking properties make it the most important grain for cooking. Its high protein content, including gluten proteins, means that the dough rises and does not collapse during baking. Both spring wheat and winter wheat are grown in Norway, with spring wheat accounting for the largest area. Oats are one of the most important cereals after barley and wheat and are grown on around a quarter of the grain area. Together, spring wheat and oats are the main cereals used for bread production in Norway and in Felleskjøpet's bread value chain. In this study the grain produced is conventionally produced. The grain is sometimes dried at farm and sometimes at storage, and in this case, it is assumed that the grain is dried at central storage.

2.4 LCA method

The approach used for the analysis is descriptive (attributional) LCA, i.e., it is an accounting LCA documenting current activities, often approximated by past (most recent) data. Therefore, this type of LCA answers the following kind of question: 'What environmental impact can be associated with this product or system?'.

LCA is in line with ISO standard 14067 which only assess GHG emissions. The LCA methodology (see Figure 1) consists of four main steps: (i) defining the purpose of the study, the functional unit, and the system boundaries; (ii) data collection that consists of obtaining information on material and energy use, emissions, and waste streams for each life cycle phase; (iii) environmental effects quantified by converting resource use, emissions, and waste into potential effects.; (iv) finally, the interpretation step, which in practice is an iterative process.

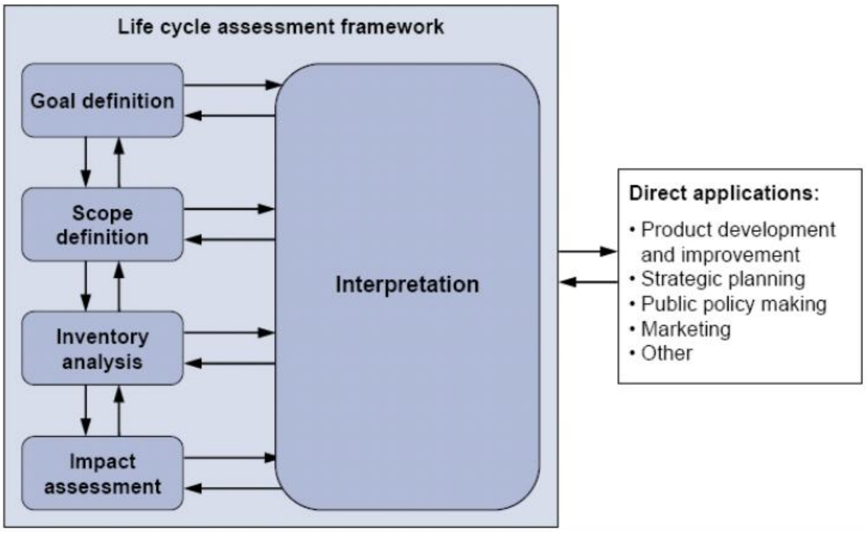


Figure 1. LCA Framework scheme based on ISO 14040:2006 (ISO, 2006a).

2.5 Functional unit and system boundaries

The functional unit is defined as 1 kg of spring wheat and 1 kg of oat grain with 15% moisture content. The reference flow corresponds to the quantity of spring wheat and oats harvested from 0.1 hectare of Norwegian fields, which produces 3.8t and 3.4t dry matter per hectare. The crops to be included in the analysis are the main ingredients for producing bread.

System boundaries and included life cycle stages for the baseline and other scenarios are from cradle-to-storage gate - see Figure 2. The system boundary begins with the production of raw materials, followed by grain production, transportation, and ending with drying at grain storage.

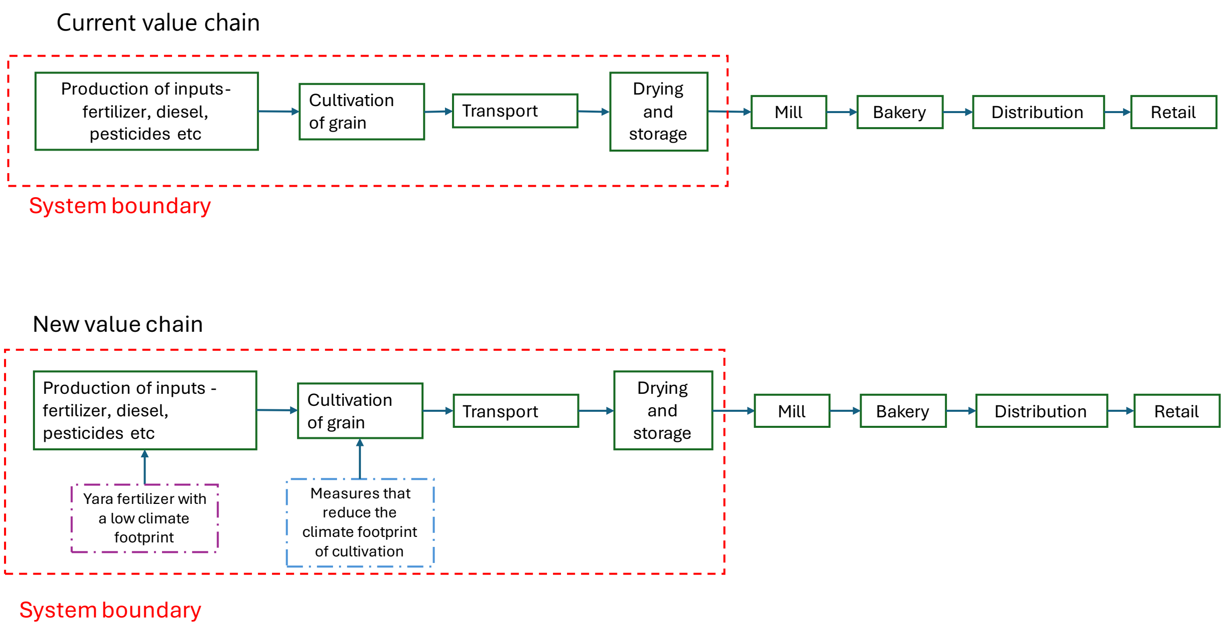


Figure 2. System boundaries of the study.

2.6 Data and data quality

The study represents the current technology used for cereal production in Norway and does not represent a specific year. The model covers Norway as geography. Baseline primary production data were obtained from available statistics, published datasets, and literature. Although some foreground fuel-use data and pesticide use originate from 2012, an assessment of current farming practices indicates that field operations, and technology have remained largely unchanged over the past decade. Given that the most influential parameters—yield and fertilizer inputs—use recent data and estimates, the dataset is considered representative of present-day production for the purpose of this CFP study. Data for grain drying and storage and transport was also taken from literature, see **Error! Reference source not found.**. Background data uses European or global t echnology where no country-specific information is available, obtained from the ecoinvent (Wernet 2016). Emissions correspond to the latest ecoinvent (Wernet 2016) database v 3.11, and calculations were done using the LCA software tool SimaPro version 10.2.0.0.

2.7 Allocation

Allocation is a method to attribute emissions and elementary flows (input and output exchanges) to products and processes and is used when multifunctional processes occur in a production system, and it is not possible to expand or subdivide the system. The background data is based on economic allocation (ecoinvent). Of the outputs 100% has been allocated to grain and 0% to straw, as a conservative approach to not underestimate the CFP.

2.8 Cut-offs, exclusions and assumptions

The LCA model is a simplification of complex systems; therefore, some assumptions have been made and are listed below:

- Capital goods were excluded from the study (e.g., buildings). Capital goods and machinery (e.g., tractors, combines, storage infrastructure) were not included in this assessment. Reliable, region-specific data on the production, maintenance, and lifetime allocation of these items are limited, and their inclusion would require complex assumptions.
- Transports of inputs to farm were not included.

Soil organic carbon (SOC) dynamics were not included in this carbon footprint assessment. Although several studies show that SOC changes can substantially influence cradle-to-farm-gate greenhouse gas emissions for cereal production, incorporating SOC requires detailed, site-specific longitudinal data and modelling approaches (e.g., IPCC Tier 2/3 methods or soil carbon models). Such data were not available within the timeframe of this study. Given the high data demand and methodological variability in SOC modelling, and consistent with common practice in many product-level LCAs, SOC was therefore excluded. This omission introduces uncertainty, particularly regarding long-term soil management effects; however, it does not affect the internal consistency or comparability of results because all systems were modelled using the same boundaries and assumptions. A more detailed assessment of SOC dynamics is recommended for future work when the required data and modelling resources are available.

Land-use change emissions were not included in this assessment. Spring wheat and oats in Norway are cultivated on long-established agricultural land, where cropland use has been stable for decades. Norway has experienced limited conversion of forest or grassland to arable land in recent history, and current cereal production primarily utilizes land that has been continuously farmed for long periods. As a result, direct land-use change emissions are considered negligible for these crops. Indirect LUC emissions were not assessed due to the lack of robust data. The biogenic uptake of carbon in the crops is not included as it is assumed to be emitted when the products are used or consumed.

Based on knowledge from experts involved in the project and previous LCA studies of cereals, the most important parts and inputs are assessed, and the main impacts have been captured in this study.

2.9 Method for carbon footprint calculation

When conducting a life cycle assessment, the collected inventory data on resources used and emissions generated are attributed to various environmental effects. This part of the life cycle assessment is called the classification.

Impact categories considered in this study are the potential contribution to climate change or Carbon Footprint.

Characterization is a way to describe the potential contribution of a resource use or an emission to a certain environmental impact. The different resources and emissions are weighted according to its potential impact in each environmental impact category. The contribution to climate change is expressed in carbon dioxide equivalents (CO_2e). For the carbon footprint, the characterization factors from IPCC (2021) GWP100 V1.03 method was used as implemented in SimaPro 10.2.0.0. multiuser version.

The United Nations Framework Convention on Climate Change (UNFCCC, 2005) describes climate change impact as an index that combines both the atmospheric lifetime of greenhouse gases and their capacity to absorb outgoing infrared radiation. Greenhouse gases themselves are vital for sustaining life on Earth, as they enable the atmosphere to retain heat. However, the large-scale combustion of fossil fuels has led to higher concentrations of these gases, intensifying heat retention and driving a marked rise in global average temperatures since the onset of industrialization. Within life cycle assessment (LCA), this phenomenon—global warming—is regarded as an environmental impact category (Lindfors et al., 1995).

The primary emissions contributing to this impact are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Their characterization factors, shown in Table 1, express their global warming potential (GWP) relative to carbon dioxide, including feedback mechanisms and are reported in the unit CO_2-equivalents. These factors are derived from the Intergovernmental Panel on Climate Change (IPCC, 2021). Uptake of biogenic carbon by crops has not been included in the calculations.

Table 1 Characterization factors (CF) used in the study for the most important contributors to climate change ((IPCC 2021) including feedback mechanisms.

Emission	CF kg CO_{2e} per kg
CO_2	1
CH_4	29,8
N_2O	273

The time horizon for the method used in this report is 100 years; other methods may use, for instance, 10 or 1 000 years, which means the characterization factors are different.

3 Life Cycle Inventory

3.1 Production of spring wheat and oat

First, a theoretical baseline for the carbon footprint of current production of spring wheat and oats was calculated based on statistics and literature data summarized in Table 2.

Table 2. Baseline data collection per input / production phase.

Farm input	Data requirement	Data source
Crop	Average of 5 years calculated	Crop data from Statistics Norway kg/0,1 ha per county or the Directorate of Agriculture's statistics. Data for spring wheat are not available. Average figures for wheat are used. Share of spring wheat of total area of wheat cultivation is 60%*
Seeds	Annual use of seeds	Hovland (2023)
Fertilizer N	Fertilization norm	Fertilizer norms accord to Kristoffersen (2025) It is assumed that all N-fertilizers are produced as BAT (Best Available Technology)
Fertilizer P	Fertilization norm	Fertiliser standards in Kristoffersen (2025)
Fertilizer K	Fertilization norm	Fertiliser standards in Kristoffersen (2025)
Fuel	Annual use, l/ha	Korsaeth, Jacobsen et al. (2012) (84 l/ha for wheat). Some of the measures mean changes in diesel use due to changes in fieldwork
Plant protection	Annual use, kg/ha	Korsaeth, Jacobsen et al. (2012)
Liming	Annual use, kg/ha	Korsaeth, Jacobsen et al. (2012), 431 kg/ha /Felleskjøpet recommendation 200-500 kg/ha
Straw removal	%	12 % according to Rønning, Byskov et al. (2023).
Waste, %	Waste %	Food waste in the agricultural sector, Norwegian Directorate of Agriculture
Leakage, N	kg N/ha	Kværnø, Fischer et al. (2024)
Leakage, P	kg P /ha	Kværnø, Fischer et al. (2024)
Nitrous oxide emissions from soil	kg N2O/ha	IPCC (2021) disaggregated
Energy	Annual use	Svanes, Oestergaard et al. (2019), (Eidem 2020)

*SSB 2025.

After the baseline analysis was performed for spring wheat and oats, the theoretical effects of measures at the farm level, calculated by NIBIO and Yara's low-carbon fertilizer, were evaluated with yield maintained as the base level. The LCA analysis included the effect of five cultivation measures and the use of the low-carbon fertilizer, discussed in the following Section 0. In **Error! Reference source not found.**, the inputs used in the model are presented. For more detailed data see Appendix 1. Emissions to air and water are shown in Table 4.

Table 3. Inputs considered in the analysis per 0.1ha.

Input	Spring Wheat	Oats	Reference
Yield, kg	449	399	SSB (2025). Average of 7 years, removed highest and lowest yields
Seeds, kg	21	20	Hovland (2023)
Net yield, kg dry weight	382	339	Calculated based on yield with 15% moisture content
Diesel, l	7.7	7.7	Korsaeth, Jacobsen et al. (2012)
Mineral fertilizer, kg P	1.8	1.8	(Kristoffersen, 2025)
Mineral fertilizer, kg K	6	6	(Kristoffersen, 2025)
Mineral fertilizer, kg N	12.5	11	(Kristoffersen, 2025)
Liming , kg CaO	42.1	42.3	Korsaeth, Jacobsen et al. (2012)
Crop residues, kg	86.3	70	76% is straw of the whole plant, 12% removed (Rønning, Byskov et al. 2023)
Herbicide, kg active ingredient	0.01	0.008	Korsaeth, Jacobsen et al. (2012)
Fungicide, kg active ingredient	0.03	-	Korsaeth, Jacobsen et al. (2012)
Insecticide, kg active ingredient	-	0.0001	Korsaeth, Jacobsen et al. (2012)
Growth regulator, kg, active ingredient	-	0.038	Korsaeth, Jacobsen et al. (2012)

Table 4. Emissions to air and water included in the analysis per 0,1 ha.

Emissions to air	Spring wheat	Oats	Source
Direct N2O emissions, kg N2O	0.32	0.37	Calculated according to IPCC 2021, disaggregated
Indirect N2O emissions, kg N2O	0.10	0.10	Calculated according to IPCC 2021, disaggregated
Emissions to water			
N leakage, kg N	5.0	5.0	National average estimate used directly from (Kværnø, Fischer et al. 2024)
N leakage as NO3 (nitrate), kg	22.25	22.25	Calculated from N leakage, kg N, according to IPCC 2021
P leakage, kg PO4-P	0.31	0.31	National average estimate used directly from (Kværnø, Fischer et al. 2024)
Ammonia emissions from mineral fertilizer, kg NH3	0.09	0.11	Calculated according to IPCC; 2021

3.2 Transport to grain storage

Transport to grain storage was based on transport distances in Korsaeth et al., 2012. The transport distance was set at 80 km with a 32t lorry on EURO 6 level. Empty returns were assumed as this information was not available.

3.3 Grain storage

It is assumed that the grain is dried at storage even if it may be dried on farm, but that information was not available for this study. Data on energy use were taken from literature (Eidem, 2020) and data can be seen in Table 5.

Table 5. Data inputs for the drying stage per kg dried grain.

Input	Spring Wheat	Oats	Reference
Oil drying, l	0.004 l/kg	0.004 l/kg	Eidem (2020)
Electricity, drying, kWh	0.008 kWh/kg	0.008 kWh/kg	Eidem (2020)
Propane, kg	0.0027 kg/kg	0.0027 kg/kg	Eidem (2020)
Pellet, kg	0.0046 kg/kg	0.0046 kg/kg	Eidem (2020)
Water emissions to air	0.0625 kg/kg	0.0625 kg/kg	Eidem (2020)

3.4 Greenhouse gas reduction measures

The Norwegian Institute of Bioeconomy Research estimated GHG-reducing potentials for on-farm measures[1], presented in **Error! Reference source not found.**, which were incorporated in NORSUS c arbon footprint calculations. Note that negative emissions in Table 6 means increased emissions.

Table 6. Potential GHG-reducing measures, estimated by NIBIO. Negative figures mean increased emissions.

Measure	Reduced N-leaching (kg N/ 0,1 ha/ yr)	Reduced N_2O loss (kg CO2e /0,1 ha/ yr)	Increased Soil Carbon (kg CO2e/ 0,1 ha/ yr)	Reduced CO_2 Emissions (kg CO2e0,1/ ha/yr)	Total Climate Effect (kg CO2e/ha/yr)	Yield Increase (%)
Soil compaction course		10		1.7 (1.4-2.0)	11.7	15 (0-50)
Split fertilization	0.3 (0–1)	1.4	–	-0.45	1	2 (0–7)
Precision spreading / section control	0.2	1		-0.45	0.5	5
No straw removal (100% area)	-	9 (6-12)	–	-	9*12%	-

Implementing practices to reduce soil compaction can decrease N_2O emissions, due to improved soil aeration and reduced denitrification, while also slightly lowering CO_2 emissions through reduced fuel consumption from fewer passes, less intensive tillage, and minimized formation of tractor ruts.

Split fertilization can reduce N_2O emissions through decreased nitrogen leaching during periods of low crop demand, while slightly increasing CO_2 emissions due to the additional fuel use required for the second fertilizer application.

Using precision fertilization with section control can reduce N_2O emissions by lowering fertilizer application and associated nitrogen losses, while also slightly decreasing overall input use; the effect on CO_2 from machinery fuel use is negligible.

Retaining straw on the field increases soil carbon storage and reduced net CO_2 emissions and also lowers N_2O emissions by immobilizing nitrogen in the straw and soil, while changes in fuel-related CO_2 emissions are negligible compared with removal operations. Since the carbon storage potentials are uncertain, only the effects on N_2O emissions are quantified in this measure.

The measure of using YARA-low carbon fertilizer was also included in the study. The CFP of the YARA low-carbon fertilizer was supplied by YARA. The fertilizer contains nitrogen (N), phosphorus (P), and potassium (K). Emission data was declared as, 0.18 tCO_2e/t Nitrogen. In comparison the BAT fertilizer used in the baseline scenario had a CFP of 4.6 tCO_2e/t product (Ammonium nitrate, as N (RER)| ammonium nitrate production | Cut-off, U, BAT, from ecoinvent 3).

[1] Norwegian Institute of Bioeconomy Research, NIBIO. Henriksen, T., Seehusen, T., Byers, E. Borg, P., 2025. Vurdering av tiltak ved produksjon av «Klimabrød». Unpublished internal document.

3.5 Sensitivity analysis

A sensitivity analysis was conducted to evaluate two key factors influencing the environmental performance of cereal production (Korsaeth, Jacobsen et al. 2012, Svanes, Oestergaard et al. 2019).

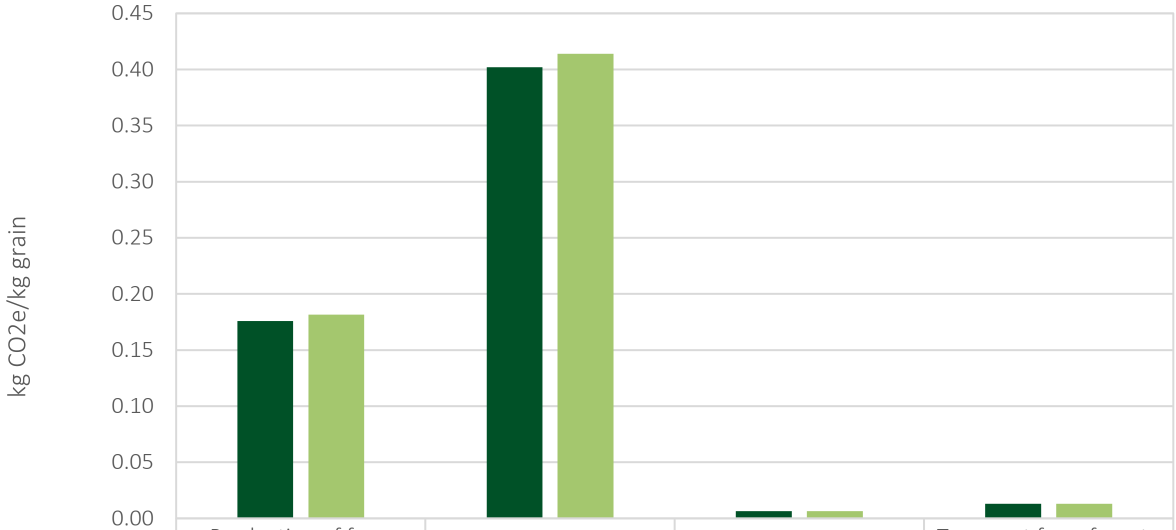
The first scenario assessed the effect of a 15 % yield reduction compared with the baseline average. Yield decreases of this magnitude may result from climatic variability, water or temperature stress, or biological factors such as pests and diseases. The reduced-yield scenario corresponded to 3,9 kg/ha/year for spring wheat and 3,3 kg/ha/year for oats.

The second scenario examined the impact of straw removal, using the minimum and maximum total climate effects estimated by NIBIO—3.6 and 7.2 kg CO_2-eq/ha/year, respectively. Straw removal is a common practice but can influence soil carbon dynamics and long-term soil quality. Only reduction of N_2O emissions due to N immobilization is estimated in this measure, and not effects in SOC dynamics.

4 Results

4.1 Current production of spring wheat and oats

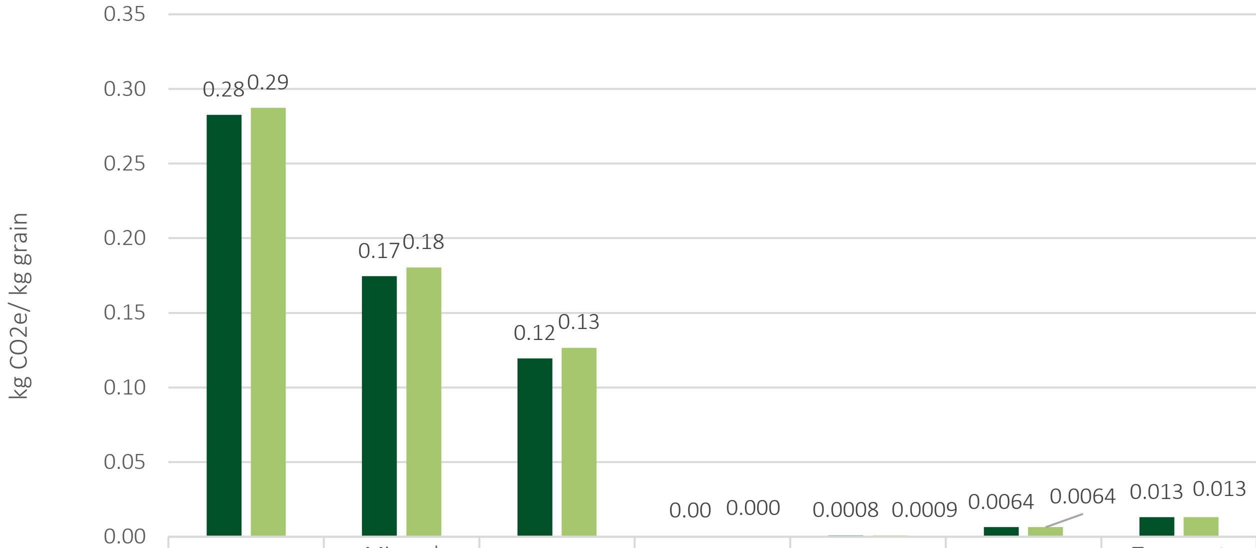
The baseline carbon footprint was estimated at 0.60 kg CO2e/kg grain and 0.62 kg CO2e/kg grain for spring wheat and oats respectively. Figure 4 shows the CFP of both crops for the life cycle stages included in the study.



	Production of farm inputs	Cultivation of grain	Storage-drying of grain	Transport from farm to storage
Spring wheat	0.18	0.40	0.006	0.013
Oat	0.18	0.41	0.006	0.013

Figure 3. Carbon footprint of Spring wheat and oat for the life cycle stages included in the study.

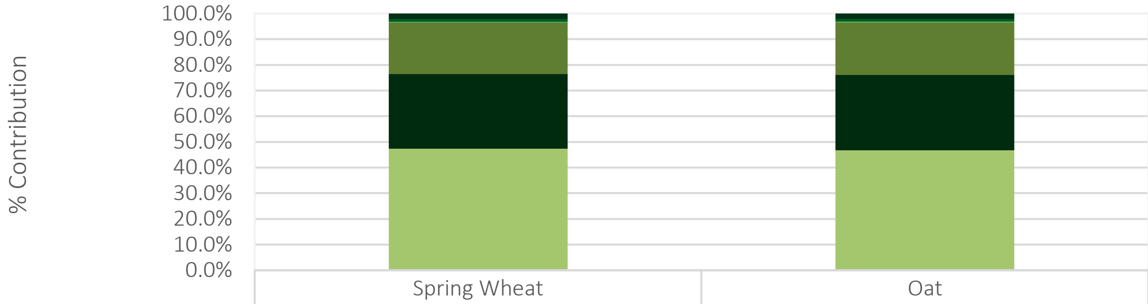
Figure 4 shows the CFP in more detail for the farm stage/crop production stage.



	Field emissions	Mineral fertilizer production	Field operations	Plant protection	Lime	Storage-drying of grain	Transport from farm to storage
Spring Wheat	0.28	0.17	0.12	0.00	0.0008	0.0064	0.013
Oat	0.29	0.18	0.13	0.000	0.0009	0.0064	0.013

Figure 4. Carbon footprint results for spring wheat and oats divided into different parameters for the farm stage.

The largest emission sources were field emissions (≈47%) and fertilizer production (≈30%), followed by field operations (≈20%). Other processes such as plant protection, drying of grain, and transport contributed less than 2%, see Figure 5.



	Spring Wheat	Oat
Transport from farm to storage	2.2%	2.1%
Storage-drying of grain	1.1%	1.0%
Lime	0.1%	0.1%
Plant protection	0.1%	0.1%
Field operations	20.0%	20.6%
Mineral fertilizer production	29.2%	29.3%
Field emissions	47.3%	46.7%

Figure 5. Percentage contribution to the CFP for spring wheat and oats.

4.2 Potential effects of reduction measures

The potential effects of the analyzed reduction measures are presented in Table 7 and Table 8 for each measure implemented separately, considering the baseline yield and the projected increments. Calculations were performed according to the NIBIO estimations and do not consider possible interaction effects, but the effects have been summarized. The potential reduction effects range from less than 0.2% implementing precision spreading up to 20% for the use of low-carbon fertilizer.

Table 7. Results of implemented measures for the baseline scenario.

	Spring wheat			Oats		
Measure	Yield, kg/ 0,1 ha	CFP (kg CO2e /kg)	Reduction (%)	Yield, kg/ 0,1 ha	CFP (kg CO2e/ kg)	Reduction (%)
Baseline	449	0.60	-	399	0.62	-
Soil compaction course	449	0.58	-4.3%	399	0.59	-4.8%
Split fertilization	449	0.60	-0.40%	399	0.61	-0.40%
Precision spreading / section control	449	0.60	-0.20%	399	0.61	-0.20%
No straw removal*	449	0.60	-0.40%	399	0.61	-0.40%
Low-carbon YARA fertilizer	449	0.48	-20.4%	399	0.49	-20.0%
Total measures	**449**	**0.45**	-25.7%	**399**	**0.46**	-25.8%

*Since carbon storage potentials are uncertain, only the effects on N_2O emissions are quantified in this measure

The potential effect of yield increases was evaluated for the measures soil compaction reduction, split fertilization, and precision spreading. Although possible interaction effects between measures were not modelled, their individual impacts were summarized. Assuming a yield increase, the mitigation potential of these measures improves substantially; for example, the benefit of precision spreading rises from 0.2 % to approximately 5%.

Table 8. Results of measures implemented and changes in crop yield as estimated by NIBIO.

	Spring wheat			Oats		
Measure	Yield, kg/ 0,1 ha	CFP (kg CO2e/kg)	Reduction (%)	Yield, kg/ 0.1 ha	CFP (kg CO2e/ kg)	Reduction (%)
Baseline	**449**	**0.6**	**-**	399	**0.6**	**-**
Soil compaction course	517	0.5	-17%	459	0.5	-17%
Split fertilization	458	0.6	-2%	407	0.6	-2%
Precision spreading / section control	472	0.6	-5%	419	0.6	-5%
Total measures	**517**	**0.4**	**-35%**	**459**	**0.4**	**-36%**

In short, individual mitigation measures have the potential to reduce the carbon footprint to varying extents:

- Precision spreading and straw removal: minor reduction (0.2–4.8%) without/with yield increase
- Split fertilization: small reduction (0.4–2%)
- Soil compaction correction: moderate reduction (4.3–17%)
- Low-carbon fertilizer: substantial reduction (20%)

Combining measures could theoretically reduce the carbon footprint by 26 when not including potential yield increase and up to–36 % when including potential yield increase compared with the baseline scenario, although this estimate assumes no interaction effects among measures.

4.3 Sensitivity analysis

In the first sensitivity scenario, a 15 % reduction in yield was assumed. Compared with the baseline, this resulted in a 17 % increase in GHG emissions, corresponding to a CFP of 0.68 kg CO2e/kg and 0.69 kg CO2e/kg for spring wheat and oats respectively. Because the results are expressed per kilogram of product, the relative reduction percentages for the mitigation measures remained unchanged, but the absolute emissions reductions per kilogram increased (Table 9).

Table 9.Carbon footprintfor spring wheat and oats with reduced yield scenario.

	Spring wheat		Oat	
Measure	CFP (kgCO2e/kg)	Reduction (%)	CFP (kgCO2e/kg)	Reduction (%)
Soil compaction course	0.68	-4.3%	0.69	-4.8 %
Split fertilization	0.70	-0.40 %	0.72	-0.40 %
Precision spreading	0.70	-0.20 %	0.72	-0.20 %
No straw removal	0.70	-0.40 %	0.72	-0.40 %
Yara low-carbon fertilizer	0.56	-20.5 %	0.58	-20.1%

The second scenario examined the effect of retaining straw on the field rather than removing it. Based on NIBIO's estimates, the potential climate effect of straw removal ranges between 6 and 12 kg CO2e/0.1 ha/year (Table 10). In the baseline scenario, retaining straw reduced the total climate effect by approximately 0.4 % compared to full removal (0.60 CO2e/kg and 0.61 CO2e/kg for spring wheat and oats respectively). Applying the minimum and maximum estimates from NIBIO, the reduction ranged from 0.3 % to 0.5 % for spring wheat and 0.3 % to 0.6 % for oats relative to the baseline.

Table 10. Sensitivity scenario results for estimated total climate effects of not removing the straw.

Crop	Straw removal	Total climate effect (kg CO2e/0.1ha/yr)	CFP (kg CO2e/kg crop)	Reduction (%)
Spring wheat	Base case	9 * 12%	0.60	-0.40 %
	Minimum	6 * 12%	0.60	-0.27 %
	Maximum	12 * 12%	0.60	-0.53 %
Oats	Base case	9 * 12%	0.61	-0.44 %
	Minimum	6 * 12%	0.61	-0.29 %
	Maximum	12 * 12%	0.61	-0.59%

5 Discussion

The discussion section starts with putting the baseline results into context by summarizing previous studies on the carbon footprints of spring wheat and oats on Norwegian and European level and comparing them to our results. After, follows a discussion of the effects of measures, the sensitivity analysis and limitations of the study.

5.1 Carbon footprints of spring wheat and oats

Although only a few European-level studies are included here (Table 11), our results for the CFP of spring wheat and oats fall within the reported ranges.

In Norway, Korsaeth et al. (2012) studied 93 farms and found that the CFP of Norwegian cereal production was 0.88–1.00 kg CO_2-eq/kg DM with spring wheat and oats having a FCP of 0.96 and 0.99 kg CO_2-eq/kg DM respectively. Emissions were mainly driven by field processes, which accounted for more than half of the total impact. About 46% of these originated from losses in soil organic carbon (SOC), while N_2O emissions from fertilizer use were the other major contributor; CH_4 emissions were negligible. Machinery and buildings contributed to 20% of the overall CFP, with manufacturing of machinery contributing more than that of buildings, 60/40 % contribution within its category.

Similarly, Bonesmo, Skjelvåg et al. (2012) reported average GHG intensities of 0.62–0.81 kg CO_2-eq/kg dry matter (DM) for cereals based on data from 95 Norwegian farms. Spring wheat again had the highest GHG intensity (0.81 kg CO_2-eq/kg DM), while oat had one of the lowest (0.64 kg CO_2-eq/kg DM). Across crops, soil N_2O emissions were the dominant source (45–49%), followed by off-farm input manufacturing (23–27%), and on-farm fuel use (10–14%). Although soil carbon changes contributed less to total emissions, they were the main driver of variability among farms, together with differences in yield, nitrogen use, and soil management. Farms with higher yields and nitrogen-use efficiency had lower GHG emissions per kg product, highlighting these as key mitigation levers.

The results of this study are generally lower than those reported. Two main methodological choices contribute to this difference. First, SOC dynamics were not included due to the lack of site-specific, longitudinal data required for reliable modelling. SOC changes can substantially influence the greenhouse gas balance of cereal production, and their exclusion introduces some uncertainty. Second, capital goods and machinery (e.g., tractors, combines, storage infrastructure) were also excluded. While the contribution of machinery is typically smaller than that of fertilizers or soil emissions, it is not negligible, and its omission further reduces total carbon footprint estimates relative to studies that include these elements. Together, these exclusions highlight that the absolute values reported here should be interpreted with caution; however, the internal consistency of the analysis and the relative comparison of reduction measures remain valid. Future work incorporating SOC dynamics and representative machinery datasets would improve comparability and provide a more complete assessment of emissions

Table 11. Summary of selected CFP of spring wheat and oats from European countries and Norway and the results from this study at the bottom of the table. Kg DM refers to 15% moisture content. If DM is different than 15% moisture content it is stated in the table.

STUDY / SOURCE	COUNTRY / REGION	CROP	GHG EMISSIONS (KG CO2E/KG)	FUNCTIONAL UNIT / NOTES	SYSTEM BOUNDARIES
KORSAETH, JACOBSEN ET AL. (2012)	Norway	Spring wheat	0.99	Per kg grain DM	Includes SOC changes, machinery & buildings
KORSAETH, JACOBSEN ET AL. (2012)	Norway	Oats	0.96	Per kg grain DM	Includes SOC changes, machinery & buildings
BONESMO, SKJELVÅG ET AL. (2012)	Norway (95 farms)	Spring wheat	0.81	Per kg DM (mean) (DM not specified)	Includes off-farm inputs; SOC changes included as variability driver
BONESMO, SKJELVÅG ET AL. (2012)	Norway (95 farms)	Oats	0.64	Per kg DM (mean) (DM not specified)	Includes off-farm inputs; SOC changes included as variability driver
RAJANIEMI, MIKKOLA ET AL. (2011)	Finland / Literature	Spring wheat	0.57–0.59	Per kg grain DM 86% (literature compilation)	Boundaries vary; often narrower than farm-gate LCAs
WILLIAMS, AUDSLEY ET AL. (2010)	United Kingdom	Wheat (incl. spring)	≈0.70	Per kg grain DM 86%	Often excludes SOC and infrastructure
THIS STUDY	Norway	Spring wheat	0.60	Per kg grain DM	Did NOT include machinery, buildings, SOC changes
THIS STUDY	Norway	Oats	0.62	Per kg grain DM	Did NOT include machinery, buildings, SOC changes

5.2 Potential effects of reduction measures and sensitivity analysis

The analysis of the potential reduction measures shows that there is potential to reduce the carbon footprint of spring wheat and oats, but that the potential effect is very variable. The implementation of low-carbon fertilizer demonstrated the potential to reduce emissions by up to 20% showing the importance of reducing production emissions from farm inputs.

The sensitivity analysis revealed a considerable increase in emissions (up to 17%) when factoring in scenarios of reduced yield by 15%. This scenario illustrates the vulnerability of agricultural emissions to external environmental conditions, highlighting the importance of yield stability for carbon footprint mitigation measures to have a significant effect.

5.3 Limitations and uncertainties of the study

While this study provides a robust assessment of the carbon footprint of Norwegian spring wheat and oat production, several limitations should be acknowledged when interpreting the results.

5.3.1 Uncertainties related to IPCC Tier 1 emission factor for N_2O

Uncertainty is an important factor when interpreting the mitigation potentials estimated in this study. Several of the assessed measures, particularly those with relatively small effect sizes (e.g., straw removal), fall within the range of uncertainty associated with key emission parameters. For instance, the IPCC Tier 1 emission factor for N_2O carries substantial inherent variability, which can exceed the magnitude of some of the estimated mitigation effects. This implies that while the direction of change remains informative, the absolute size of certain mitigation potentials should be interpreted with caution. Measures with larger and more robust effects—such as the use of low-carbon fertilizers—are less affected by this uncertainty. Future work incorporating higher-tier (Tier 2 or Tier 3) N_2O modelling or region-specific emission factors would improve the precision of mitigation estimates.

5.3.2 System boundaries and excluded processes

The system boundaries were defined as cradle-to-storage gate and did not include emissions related to machinery, buildings, or infrastructure. These capital goods are often excluded in agricultural LCAs due to limited data availability and their relatively small contribution to total emissions; however, including them would likely increase the absolute carbon footprint values slightly.

Similarly, changes in soil organic carbon (SOC) were excluded. SOC dynamics can represent a significant source or sink of greenhouse gases, depending on management practices and soil type. Excluding SOC changes introduces uncertainty and may underestimate or overestimate total emissions depending on local soil conditions.

5.3.3 Interactions between mitigation measures

The potential combined effects of mitigation measures were estimated by summing the individual reductions, without modeling possible interactions. Measures may reinforce or counteract each other, leading to either higher or lower combined effects than reported. Therefore, the total reduction potential of 25–35 % should be regarded as indicative rather than additive.

5.3.4 Data sources and representativeness

Most input data were derived from literature and national statistics, reflecting average Norwegian conditions. Although the most recent and relevant datasets were used, they do not fully capture regional variability, farm-level management differences, or year-to-year fluctuations in yields and emissions. The use of secondary data also limits the ability to validate results against primary measurements. No comprehensive yield statistics are available for spring wheat in Norway. To address this, we used national wheat yield data over the last 10 years (2014–2024), excluding the highest and lowest values to reduce the effect of extreme years, resulting in an average based on 7 years. While spring wheat may have somewhat lower yields, this approach provides a reasonable estimate of average production conditions. The potential impact of this substitution on the carbon footprint results is expected to be small, given that fertilizer application rates, general agronomic practices, and input use for wheat are similar across the main wheat types grown in Norway.

5.3.5 Emission modeling assumptions

Calculations of nitrous oxide (N_2O) emissions from soils followed the IPCC (2021) Tier 1 methodology, which applies generic emission factors. Tier 1 factors are not country-specific and therefore may not accurately represent Norwegian climatic and soil conditions. Likewise, the model relies on non–crop-specific emission factors for nitrogen leaching to water, which adds further uncertainty to the nutrient loss and indirect N_2O estimates.

5.3.6 Limitation to carbon footprint assessment

A limitation of this study is that it is restricted to the carbon footprint in accordance with ISO 14067 and does not assess other environmental impact categories, such as eutrophication, acidification, or biodiversity impacts, which may be relevant for a more comprehensive environmental evaluation.

5.3.7 Overall implications

These limitations imply that the results should be interpreted as indicative estimates of relative performance and potential improvement, rather than precise absolute values. Future work should aim to refine the model by incorporating country- and crop-specific emission factors, SOC dynamics, and empirical data from farms implementing the measures, as well as by quantifying uncertainty and interactions between measures.

6 Conclusions

This study quantified the carbon footprint of Norwegian spring wheat and oat production and assessed the theoretical reduction potential of several greenhouse gas mitigation measures at the farm level. The analysis represents an average of current Norwegian conditions and provides an indicative baseline for evaluating and communicating climate performance in Felleskjøpet’s bread value chain.

The baseline carbon footprint was estimated at 0.60kg CO_2e/kg for spring wheat and 0.62 kg CO_2e/kg for oats. These values are within, or slightly below, the ranges reported in previous Norwegian and European studies, largely due to the narrower system boundaries applied. Emissions were dominated by field processes (≈47 %) and fertilizer production (≈30 %), followed by fuel use (≈15 %).

Among the individual mitigation measures assessed, low-carbon fertilizer showed the highest reduction potential (≈20 %), while measures related to soil compaction reduction, split fertilization, and precision spreading offered smaller reductions, particularly when yield increases were assumed. The total combined effect of the measures was a reduction potential of up to 26% without considering potential yield increases and up to 36% taking yield increase into account. None of the estimates considered possible interactions between the measures.

The sensitivity analysis indicated the importance of maintaining stable yields. A 15 % yield reduction increased the carbon footprint by approximately 17 %, while straw retention could reduce GHG emissions by up to 0.6 % per kg of product depending on the assumptions about soil carbon storage. These results highlight the dual importance of yield stability and soil management in achieving low GHG intensities in cereal production.

Despite the robustness of the methodological approach, several limitations should be acknowledged. The exclusion of machinery, buildings, and soil carbon stock changes likely underestimates total emissions. Moreover, the results rely on literature-based data and Tier 1 IPCC emission factors, which do not fully capture Norwegian or crop-specific conditions. Finally, potential interactions between mitigation measures were not modeled, meaning the combined reduction potential is indicative rather than definitive.

In conclusion, this study indicates that carbon footprint reductions in Norwegian cereal production are achievable.

Further work should focus on empirical validation of these measures on Norwegian farms, refined emission modeling with Tier 2 or Tier 3 data, include more environmental impact categories and integration of soil carbon and interaction effects to strengthen the accuracy of future assessments.

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Appendix 1

Table 0-1. Norm yield 5 years (highest and lowest excluded), kg per 0,1 ha, 15% moisture content, (SSB 2025)

Year	Spring wheat	Oat
2017	529	418
2018	235	224
2019	560	417
2020	477	474
2021	417	393
2022	532	507
2023	291	293
Average yield	449.2	399

Table 0-2. Average input of seeds per 0,1 ha (Hovland 2023).

Cereals	kg per 1000 m²	Avg
Spring wheat (550 plants per m²)	18–24	21
Oats (525 plants per m²)	18–23	20.5

Table 0-3. Fertilization norms for N, P and K for the cereal crops (Kristoffersen 2025).

Crop	Expected yield (kg/0.1ha)	Fertilization norm (kg/0.1ha)			Change in N/P/K per 100 kg yield change)		
		N	**P**	**K**	**N**	**P**	**K**
Oats	500	11.1	1.75	6.00	1.6	0.35	1.00
Spring wheat, food	500	12.5	1.75	6.00	1.6	0.35	1.00

Table 0-4. Straw crops (10cm) (Hovland 2023).

Grain Type	Straw/Grain Ratio	Straw/Grain Ratio with Growth Regulation
Oats	0.76 (0.58 - 0.91)	0.64
Spring wheat	0.92 (0.85 - 1.17)	0.74

Table 0-5. Inventory cradle to farm assessment in (Korsaeth, Jacobsen et al. 2012).

Parameter	Oat	Spring Wheat
Number of fields	61	50
Yield, t ha^{-1} (0.85% DM)	3.86 (0.47)	4.01 (0.47)
Straw to grain ratio (t DM t^{-1} DM)	0.64	0.74
N-fertilizer[b], kg ha^{-1}	109 (7.33)	92.6 (0.76)
N-fertilizer[c], kg ha^{-1}	0	31.2 (3.79)
Lime, kg ha^{-1}	423 (13.1)	421 (10.2)
Chemical fallow[d], kg ha^{-1}	0.93	0.93
Spraying (herbicide)[d], kg ha^{-1}	0.08	0.07
Spraying (fungicide)[d], kg ha^{-1}	0	0.25
Spraying (insecticide)[d], kg ha^{-1}	<0.01	0
Spraying (growth regulator)[d], kg ha^{-1}	0.38	0
Diesel, l ha^{-1}	76.7 (3.20)	77.2 (3.23)
Initial SOC-stock, t C ha^{-1}	71.3 (12.4)	71.5 (12.7)
N-leaching, kg N ha^{-1}	30.3 (8.81)	33.6 (8.19)
P-loss, kg P ha^{-1}	1.81 (0.62)	1.84 (0.65)
Buildings (M€ yr^{-1} $farm^{-1}$)[e]	0.01	
Machinery (t yr^{-1} $farm^{-1}$)[f]	1.9	

a From Riley et al. (2012)
b Compound fertilizer with 21.6% N, 2.6% P and 9.6% K
c Containing 27% N
d Active ingredients
e Assuming a lifetime of 30 years
f Assuming lifetimes of 10–20 years (Roer et al., 2012)

Table 0-6. Different energy carriers for grain drying on farms and in receptions/mills. Proportions and quantities of cereals dried (Eidem 2020).

Fuel Type	Farms Share	Receiving Stations/Mills Share	Total Share	Quantity (Tons of Grain)
Heating oil/diesel	85 %	16 %	40 %	500 000
Propane	10 %	48 %	35 %	437 500
Wood chips/pellets	5 %	24 %	17 %	212 500
Electricity	0 %	12 %	8 %	100 000
Total	**35 %**	**65 %**	**100 %**	**1 250 000**

Table 0-7. Energy use and CO_2 emissions from different methods for drying grain (Eidem 2020).

Total Grain Drying	Farm use 35%	Reception/ Mills (65%)	Total	Tons of grain	kWh	Factor kWh/l or kg	Liters/kg	CO_2 Factor	Ton CO_2
Fuel oil/diesel - l	0.85	0.16	0.40	500 000	50 000 000	10	5 000 000	2.66	13 300
Propane - kg	0.10	0.48	0.35	437 500	43 750 000	13	3 391 473	3.00	10 174
Wood pellets	0.05	0.24	0.17	212 500	21 250 000				
Electricity	-	0.12	0.08	100 000	10 000 000	1	10 000 000		
Total	1.00	1.00	1.00	1 250 000	125 000 000				

Table 0-8. Energy consumption and greenhouse gas emissions from Norwegian grain drying (Eidem 2020).

Grain Drying Mill	Reception/ Mills (65%)	Tons of grain	kWh	Factor kWh/l or kg	Liters/kg	CO_2 Factor	Tons CO_2
Fuel oil/diesel - l	16 %	130 000	13 000 000	10.0	1 300 000	2.7	3 458
Propane - kg	48 %	390 000	39 000 000	12.9	3 023 256	3.0	9 070
Wood pellets	24 %	195 000	19 500 000				
Electricity	12 %	97 500	9 750 000	1.0	9 750 000		
Total	100.00 %	812 500	81 250 000				

Table 0-9. Propane gas consumption and associated greenhouse gas emissions on Norwegian farms (Eidem 2020).

Propane Drying Farm Use	Tons of grain	kWh	Factor kWh/l or kg	Liters/kg	CO_2 Factor	Tons CO_2
Propane - kg	43750	4375000	12.9	339147	3	1017

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