Carbon Footprint of Four Cereal Crops Produced in New Zealand

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Contents

1. Executive Summary

This report presents updated, cradle-to-gate carbon footprints for New Zealand's four principal livestock feed crops: wheat grain, barley grain, maize grain, and maize silage. The study was commissioned by the Foundation for Arable Research (FAR) and conducted by the Bioeconomy Science Institute (BSI), drawing on primary data from 23 growers and contractors across the Waikato, Lower North Island, Canterbury, and Southland regions.

This is version 2 of the report, in which the emission factors used to calculate the crops' carbon footprints were sourced from the Agri-footprint database, enabling the results to be used in the Ag:LCA dairy API. The previous version used emission factors from the ecoinvent database, but its end-user licence agreement prevents BSI from using those factors in the Ag:LCA dairy API.

The pastoral sector faces growing pressure to accurately report scope 3 emissions. These emissions are the indirect greenhouse gas emissions generated by off-site processes outside a farm's direct control. For dairy and beef operations, this includes brought-in feeds produced off-farm. The emission factors for these inputs have historically relied on broad regional averages that fail to reflect current New Zealand specific cropping practices. This study addressed that gap.

Production-weighted national average cradle-to-gate carbon footprint for dried feeds ready to be shipped, excluding emissions from drained peatland. MC = moisture content; DM = dry matter; SD = production-weighted standard deviation; CO_2e = Carbon dioxide equivalent.

Crop	Emission Factors	Weighted SD
Maize silage	0.14 kg CO_2e /kg DM	±0.04
Barley grain	0.21 kg CO_2e /kg grain (14% MC)	±0.05
Maize grain	0.24 kg CO_2e /kg grain (14% MC)	±0.03
Wheat grain	0.30 kg CO_2e/kg grain (14% MC)	±0.02

When accounting for a modelled 2.46% of maize cropping area on drained peatland, the national emission factors increase to 0.32 kg CO_2e/kg grain (14% MC) for maize grain and 0.18 kg CO_2e/kg DM for maize silage.

Across all crop types, the dominant emission sources were:

- Fertiliser and lime: Both the upstream production and transport of inputs, and on-farm soil emissions following application, consistently dominated the footprint across all crops.
- Crop residue management: Particularly significant for wheat, where 4 of 7 surveyed farms burned residues in the field, generating nitrous oxide (N_2O) and methane (CH_4) emissions and precluding straw co-product allocation.
- Drying: The most relevant for maize grain, which requires active gas-fired drying from harvest moisture (18–19%) down to the 14% storage target.
- Irrigation energy: A meaningful contributor for some farms, particularly those using diesel-powered systems; one diesel-irrigated barley farm showed three times higher irrigation emissions than its electrically powered counterpart.
- Peatland soils: A significant source only for a small proportion of maize producers farming on drained peat in the Waikato. For these growers' peat-related CO_2, CH_4, and N_2O emissions dominate the total footprint. Assuming 2.46% of maize grown in NZ is on drained peatland, this would increase the national average maize grain by 0.08 kg CO_2e /kg maize

grain (14% MC) and maize silage by 0.04 kg CO_2e /kg DM of maize silage. Carbon footprints, including peat-related emissions, would then increase to 0.31 kg CO_2e /kg maize grain (14% MC) and 0.18 kg CO_2e /kg DM of maize silage.

The updated emission factors are lower than prior AgResearch estimates (Ledgard & Falconer, 2015), with differences likely attributable to improvements in nitrogen use efficiency and crop yields, even with the inclusion of irrigation-related emissions not captured in earlier reports.

Economic allocation between grain and straw co-products was applied in accordance with IDF (2022) and FAO LEAP guidelines where straw was baled and sold. A sensitivity analysis across three allocation approaches (economic, nitrogen content and metabolisable energy) for barley showed a modest spread of 0.028 kg CO_2e/kg grain between methods, confirming that allocation methodology is not a dominant source of uncertainty for this crop.

2. Methodology

This section outlines the methodological framework of the carbon footprint using life cycle assessment (LCA) methodology. The following sections covers the goal and scope definition, life cycle inventory (LCI), and life cycle impact assessment (LCIA).

2.1 Goal and Scope

2.1.1 Goal

The goal of this study is to update cradle-to-gate carbon footprints for four livestock feed crops produced in NZ: wheat grain, barley grain, maize grain, and maize silage. These crops were selected because of they are the most significant locally produced supplementary feed source for the pastoral sector.

Previous studies from the BSI group used carbon footprint for these crops but relied on broad and dated assumptions (Ledgard & Falconer, 2015). These emission factors have been kept up to date with respect to the latest global warming potentials for inclusion into LCA modelling, but they have not been reviewed in light of current cropping practice since they were first prepared.

With growing interest in reducing scope 3 emissions from pastoral agriculture, farmers and their processors are increasingly monitoring their emissions at the farm gate. These emissions include the production of farm inputs, such as supplementary feed, which contribute materially to the farm footprint.

The arable sector encompasses a wide range of crops and production systems, making sector-wide emissions characterisation inherently complex. To address this, primary data was collected directly from local producers using production surveys. These surveys captured the actual quantities of inputs (fertiliser, fuel, pesticides etc.) and outputs (yield) used on farm to produce these feeds, ensuring the emission factors generated reflect current NZ cropping practices.

2.1.2 Scope

The scope of the current study is to estimate the total cradle-to-gate carbon footprint from the production of the four crops of interest: wheat grain, barley grain, maize grain and maize silage. The analysis focused on productions systems across the Waikato, Lower North Island, Canterbury and Southland regions, as these are the main regions where the crops of interest are grown. The difference between irrigated and non-irrigated crops was to be captured, particularly for wheat crops in mid-Canterbury. A total of twenty-four growers/contractors volunteered to take part in the study, each completing a survey for the 2024-2025 growing season. Surveys captured input and outputs at the paddock level. The data provided the basis for generating emissions factors representative of current arable production practices.

2.1.3 Functional unit

The function analysed for this carbon footprint study is the production of a crop as a supplementary feed for animal consumption. The functional unit was per kg of dry matter (DM) for maize silage and per kg of grain (14% moisture content - MC) for wheat, barley and maize grain.

2.1.4 System boundary

The system boundary extends from the production of seed used for sowing through to distribution of the harvested crop to the point of storage (Figure 1). Inventory for this LCA includes the upstream processes, i.e. the production, transportation and application of inputs (seeds, pesticides, fertilisers, and diesel) as well as the emissions from the use of these inputs. This inventory does not include farm capital.

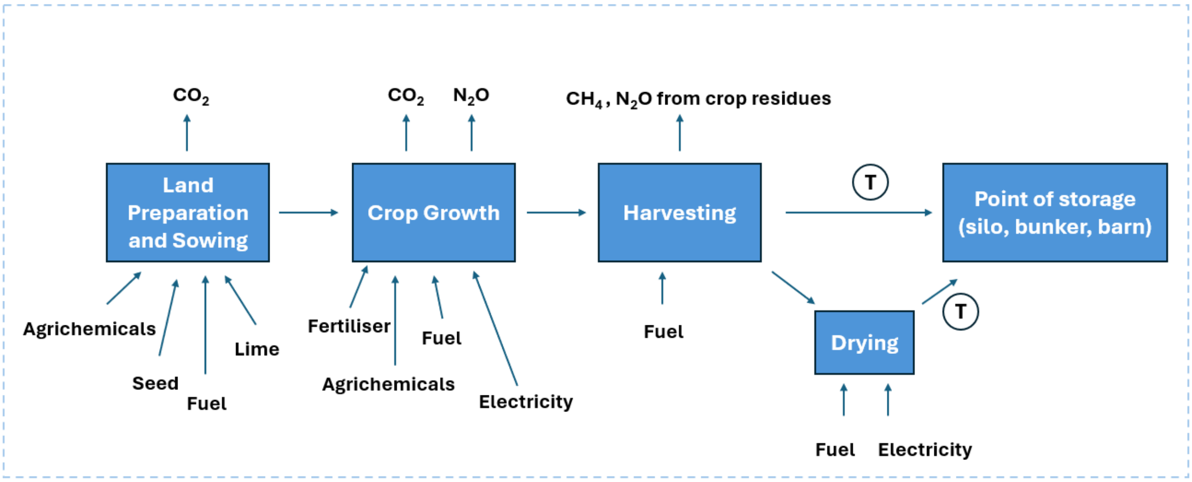

Figure 1. System boundary for the cradle-to-gate LCA of NZ arable feed crops. Each production stage is presented as a box and "T" denotes transport between stages

2.1.5 Allocation

An attributional LCA approach was used in this study and allocation between co-product was applied when producers reported balling and selling the straw. The allocation between the co-products of straw and grain was applied using an economic allocation framework, as suggested by the International Dairy Federation (IDF, 2022). If straw was incorporated or burned, no allocation was applied and all emissions were assigned to the grain. Other allocation alternatives are explored in the sensitivity analysis in Section 5.

2.2 Life Cycle Inventory

The life cycle inventory (LCI) quantifies all material and energy flows, as well as associated GHG emissions, occurring within the system boundary defined in Section 2.1.4. Input data used in this study were primarily sourced from production surveys completed by participating growers. Where primary data were incomplete or unavailable, secondary data were obtained from published literature (i.e. fuel use) and the NZ GHG inventory (MfE, 2025). Emission factors for individual inputs or process, such as pesticide production or transport, were sourced from the Agri-footprint database (Durlinger et. al., 2014). For inputs with NZ-specific characteristics, Agri-footprint background processes were modified accordingly using SimaPro software. This was particularly relevant for grain drying and irrigation, where the carbon intensity of the NZ electricity grid was substituted to better reflect local conditions. The input data sources are summarised in the following sub-sections:

2.2.1 Crop yields

The crop yields were supplied by the growers.

2.2.2 Fuel use

The carbon footprint from fuel use was calculated by combining the emissions from on-farm fuel combustion and off-farm transport. On farm fuel use was estimated using grower-supplied primary data on field work type (i.e. disking or spraying) and amount (pass per ha). For some reported operation, growers also indicated the tractor power rating (kW) for representativeness. Field operations were converted to diesel fuel consumption using operation-specific fuel-use emission factors sourced from the literature (Table 1). For off-field transport, ton kilometre (tkm) was used, representing the emissions from transporting inputs on farm (pesticide, fertiliser etc.) and transporting the harvested crop to the storage facility. For each farm and crop, total fuel use emissions were calculated as:

$$\text{Diesel}_{\text{total}} = \sum_i (\text{Pass/ha}_i \times \text{DCR}_i) \times \text{EF}_{\text{diesel}} + (\text{tkm} \times \text{EF}_{\text{transport}})$$

Where:

- *i* indexes field operations (e.g., cultivating, planting, fertiliser and lime broadcasting, plant protection spraying, and harvesting) in passes per ha (*Pass/ha*).
- DCR_i is the diesel consumption rate for each operation or transport as specified in Table 2.
- $\text{EF}_{\text{transport}}$ is the emission factor for transporting material on land, sourced from Agri-footprint.
- $\text{EF}_{\text{diesel}}$ is the emission factor for burning diesel in NZ from a modified process sourced from Agri-footprint, representing overseas diesel production and shipping to NZ.
- EF NZ-specific emissions from diesel supply and combustion.
- Tkm is for tonne per km, a unit to quantify material transport

When multiple EFs were available for the same operation, and the available information did not allow to choose a specific one, the arithmetic mean of appropriate EFs were used.

Table 2. Diesel consumption rate (DCR) for specific activities used to estimate total fuel use and data source.

Activity	DCR	Source(s)
Planting - Row Crop Planter	15.6	Average from Tassielli et al., (2019)
Planting - Grain Drill	23.1	Average from Tassielli et al., (2019)
Harvesting - Small grain	20.9	Average from Tassielli et al., (2019)
Harvesting - Forage (corn silage)	19.9	Average from Tassielli et al., (2019)
Harvesting - Corn grain	17.6	Average from Tassielli et al., (2019)
Cultivating - Disking, primary	11.6	Average from Tassielli et al., (2019)
Cultivating - Disking, secondary	8.6	Average from Tassielli et al., (2019)
Cultivating - Chisel	14.9	Average from Tassielli et al., (2019)
Cultivating - Roller	4.0	Wells (2001)
Spraying - Plant protection	2.5	Average from Nemeck and Kagi (2007) and Wells (2001)
Broadcasting - Lime or Fertiliser	2.6	Average from Nemeck and Kagi (2007); Salam et al. (2008); and ASABE (2006)
Transport	NA*	Durlinger et al., (2014)

*Transport does not need DCR as the emissions factor is given in kg of CO_2e per tkm, not L of diesel.

2.2.3 Fertilisers and lime

GHG emissions associated with fertiliser and lime inputs were accounted for across three stages: manufacture, transport, and soil application, encompassing resource extraction, beneficiation, all transportation stages, and the manufacturing process itself.

Manufacturing emission factors for each fertiliser were sourced from the Agri-footprint database using the Oceania regional markets (Durlinger et al., 2014).

Transport emission factors (kg CO_2e/tkm) for all fertiliser products within New Zealand were calculated using weighted average transport distances by region, based on Ledgard et al. (2020).

Following field application, fertilisers and lime undergo soil reactions that result in additional gas emissions, which are accounted for in the inventory and described in the sub-sections below.

2.2.3.1 Nitrous oxide emissions from nitrogen fertilisers

Calculation of the N_2O direct and indirect emissions produced after the nitrogen fertiliser is applied to soils was based on the methodology and default EFs used in the NZ GHG inventory. The NZ GHG inventory is prescribed by the International Panel on Climate Change (IPCC) methodology (MfE, 2025). The N_2O emissions come from direct and indirect sources (Table 2).

Table 2. Key emission factors (EFs) and parameters according to NZ GHG inventory (MfE 2025).

Process	Mean	References
kg of N_2O-N emitted per kg of N:		
Due to N fertiliser use (EF_1)	0.01	IPCC (2006)
Due to atmospheric deposition of NH_3 (EF_4)	0.01	IPCC (2006)
Due to leaching and runoff of NO_3 (EF_5)	0.0075	IPCC (2006)
kg of NO_3-N emitted per kg of N fertiliser applied ($FRAC_{LEACH}$)	0.07	Thomas et al. (2011)
kg of NH_3-N emitted per kg of N fertiliser applied ($FRAC_{GASF}$)	0.10	IPCC (2006)

These EFs were then multiplied by the rate of N fertiliser applied to get N_2O-N emissions per hectare. They are then multiplied by the global warming potential (GWP) characterisation factor for N_2O (273 kg CO_2e/kg N_2O) to get CO_2-equivalent emissions per hectare, as delineated in the 6th assessment report of the IPCC (Forster et al., 2021)

2.2.3.2 Carbon emissions from lime following application to soil

According to IPCC (2006) methodology, when applying lime in an agricultural soil, emissions of CO_2 from the carbonate in lime must be included when calculating total GHG emissions. When limestone (calcium carbonate; $CaCO_3$) is applied to soil, CO_2 is released over time. The EFs used is NZ specific. Based on IPCC guidelines, and assuming 93% purity of limestone in NZ, the EF equates to 0.412 kg CO_2/kg limestone. This is then multiplied by the rate of lime application to get total CO_2 emissions per hectare following the equation:

$$E_{\text{lime}} = EF_{\text{lime}} \times R_{\text{lime}} \times 0.93$$

Where:

E_{lime}= CO_2 emissions from lime application (kg CO_2/ha)

R_{lime}= lime application rate (kg lime/ha), assuming a 93% $CaCO_3$ content

EF_{lime}= emission factor for limestone (kg CO_2/kg lime)

2.2.3.3 Carbon emissions from urea following application to soil

When urea ($CO(NH_2)_2$) is applied to soil, CO_2 is released over time. The 2006 IPCC equation for the calculation of CO_2 emissions from urea is shown below.

$$E_{urea} = EF_{\text{urea}} \times R_{\text{urea}}$$

Where:

- E_{urea}= CO_2 emissions from urea application (kg CO_2/ha)
- R_{urea}= urea application rate (kg urea/ha)
- EF_{urea}=emission factor for urea (0.733 kg CO_2/kg urea), calculated as:

$$EF_{urea} = 0.2 \times \frac{44}{12}$$

An EF for urea (0.2) which accounts for the carbon content of urea (20% of $CO(NH_2)_2$ mass) is multiplied by 44/12 (conversion of elemental C to molecular CO_2).

2.2.4 Agrichemicals

It is a common practice for growers to use agrichemicals, predominantly fungicides, herbicides and insecticides. The types and amounts of agrichemicals used in the production of each crop was provided by the growers. EFs to produce these agrichemicals were sourced from Agri-footprint (Durlinger et al., 2014) while emissions from transport and on-field spraying were included in the fuel use (see section 2.2.2; Table 2 “Spraying – Plant Protection”)

2.2.5 Irrigation

Energy and/or fuel use required to power irrigators were also included. Emissions from irrigation were calculated based on energy consumption. Farm surveys were able to give (1) total volume of water or diesel used in the growing season and (2) discriminate between fossil fuel and electricity powered irrigation. All farms using diesel powered irrigation had information regarding total volume of diesel consumed over the season. Farms using electricity-powered irrigation also reported the total volume of water used during the season. First principles were used to model the energy consumption and resulting emissions from a sprinkler type irrigation system powered by the NZ electrical grid.

2.2.6 Crop residues

After the crop has been harvested, crop residues remain. These are either incorporated back into the soil, baled and stored or sold, and in some cases burned. The IPCC (2006) guidelines for national GHG inventories (tier 2 and tier 3) are used to account for the N_2O emissions from the degradation of the crop residues from above and below ground tissues.

For above-ground residues, New Zealand commonly applies a modified approach proposed by Thomas et al. (2011; 2012), because the standard IPCC linear regression was found to be unsuitable for NZ conditions. Instead, the amount of above-ground dry matter is estimated using the harvest index method, which links residue biomass to the harvested crop yield. Emissions of N_2O from the decomposition of these residues are then calculated following the IPCC Tier 2/Tier 3 EFs used in the NZ GHG Inventory.

A critical distinction occurs when residues are burned. While the biogenic CO_2 released during combustion is considered carbon-neutral, burning is a significant source of net anthropogenic emissions, including both N_2O and CH_4. Unlike decay-based emissions which are calculated from nitrogen pools, CH_4 emissions from burning are determined by the amount of carbon released from the consumed biomass (MPI, 2025; MfE 2025).

Specifically, CH_4 is calculated by multiplying the biomass burned by the carbon fraction of the residue, the fraction of biomass oxidised, and a gas-specific emission ratio. This ensures the inventory captures the potent warming effect of CH_4 produced by incomplete combustion, which would not occur if the residue were left to decay naturally (Thomas et al., 2011; Thomas et al., 2012).

2.2.7 Drying

Moisture content at harvest ($MC_{harvest}$) was acquired in the survey. A drying process was modelled when $MC_{harvest}$ exceeded the target storage moisture of 14% (MC_{target}). The amount of moisture to be removed ($Water_{removed}$, in kg) was calculated as:

$$Water_{removed} = Y \times MC_{harvest} - Y \times MC_{target}$$

Where:

- $Water_{removed}$= mass of water to be removed during drying (kg)
- Y= yield, fresh mass (kg)
- $MC_{harvest}$= moisture content at harvest (fraction of fresh mass)
- MC_{target}= target storage moisture content (0.14)

Drying emissions were modelled using datasets from Agri-footprint (Durlinger et al., 2014). According to industry expert, maize grain drying is typically a more energy-intensive process powered by natural gas compared with barley and wheat. Maize is often harvested at higher moisture content and therefore requires active heated drying. In contrast, barley and wheat are usually harvested closer to the target storage moisture; when drying was required, it was assumed to occur through lower-intensity aeration using forced air in on-farm silos. Accordingly, emissions from drying were modelled using modified versions of the following: “drying of feed grain” using natural gas combustion and the “drying of feed grain – ambient air” modified with a NZ electricity grid mix to represent fan-assisted aeration.

2.2.8 Peatland emissions

For wheat and barley, peat-related emissions were not considered. Production of these crops is concentrated in mineral soil, as confirmed by governmental sources and industry experts (Pers. com. FAR; MfE, 2025; Leathwick et al., 2002). Conversely, maize is known to be grown on drained peatland, as seen in our samples and confirmed in other references where it is reported that maize production in NZ is concentrated in the Waikato region, which contains approximately half of NZ total peatland area, much of which has been drained for agriculture (Dresser et al., 2012).

Emissions from drained peatland were modelled based on reported areas from the NZ GHG Inventory and Statistic NZ. The total area of annual cropland in NZ is 389,133 ha and the total area of organic soils under annual cropland is 7,300 ha (MfE 2025). Under the assumption that only maize-producing farms could be found drained peatland, we subtracted the total area of wheat (46,400 ha) and barley (46,200 ha) from the reported total area of annual cropland (StatsNZ, 2025). This gives a revised area of annual cropland that could be on drained peatland to 296,533 ha. Taken together, these assumptions provided a 2.46% factor for computing annual cropland, excluding wheat and barley, that is on drained peatland. The resulting CO_2, N_2O, and CH_4 emissions from these soils are summarised below.

2.2.8.1 N_2O emissions

N_2O emissions are estimated by multiplying the area of organic soils by a default EF for Grassland, drained, nutrient poor of 4.3 kg $N\text{-}N_2O$/ha/yr (IPCC 2014).

2.2.8.2 CO_2 emissions

CO_2 emissions are estimated by multiplying the area of organic soils by a default EF for Grassland, drained, nutrient poor of 5.3 tC-CO_2/ha/yr (IPCC 2014).

2.2.8.3 CH_4 emissions

A Tier 1 approach is used by multiplying the area of organic soils by the default EF value for Grassland, deep-drained, nutrient rich (there is no deep-drained nutrient-poor option) in a warm temperate climate of 16 kg CH_4/ha/yr. (IPCC, 2014). The IPCC 2014 methodology also assumes that 5% of the peat area is in ditches and assigns an EF of 1165 kg CH_4/ha/yr to this area.

2.3 Impact Assessment Method

The carbon footprint (equivalent to Global Warming Potential [GWP]) was calculated according to IPCC AR6 guidelines (Forster et al., 2021). GWP indicates the potential of a greenhouse gas to trap extra heat in the atmosphere over time. The enhanced heat trapping in the atmosphere (the "greenhouse effect") is caused by the absorption of infrared radiation by a given gas. GWP100 is based on energy absorbed over 100 years. Each greenhouse gas has a specific GWP, which is used to calculate the carbon dioxide equivalent (CO_2e) by multiplying the mass of gas emitted by its GWP. GWP100 has multiplication factors of 1 for CO_2, 273 for N_2O, 29.8 for fossil CH_4 and 27 for biogenic CH_4.

3. Results and Discussion

3.1 Individual Farm Results

The carbon footprint for each crop was evaluated at the individual-farm level. The farm-specific total emissions intensity is presented as stacked process contributions, allowing direct comparison among farms and across regions for each crop. Unlike a single national mean, these results highlight the spread in farm performance and the process drivers behind that variation. Results for farms producing barley (Figure 2A), wheat (Figure 2B), maize grain (Figure 2C) and maize silage (Figure 2D) are presented below. Without looking at peat-related emissions, the lowest observed carbon footprint was observed for maize silage (0.08 – 0.23 kg CO_2e/kg DM), while the highest carbon footprint was found in wheat (0.26 – 0.40 kg CO_2e/kg grain 14% MC).

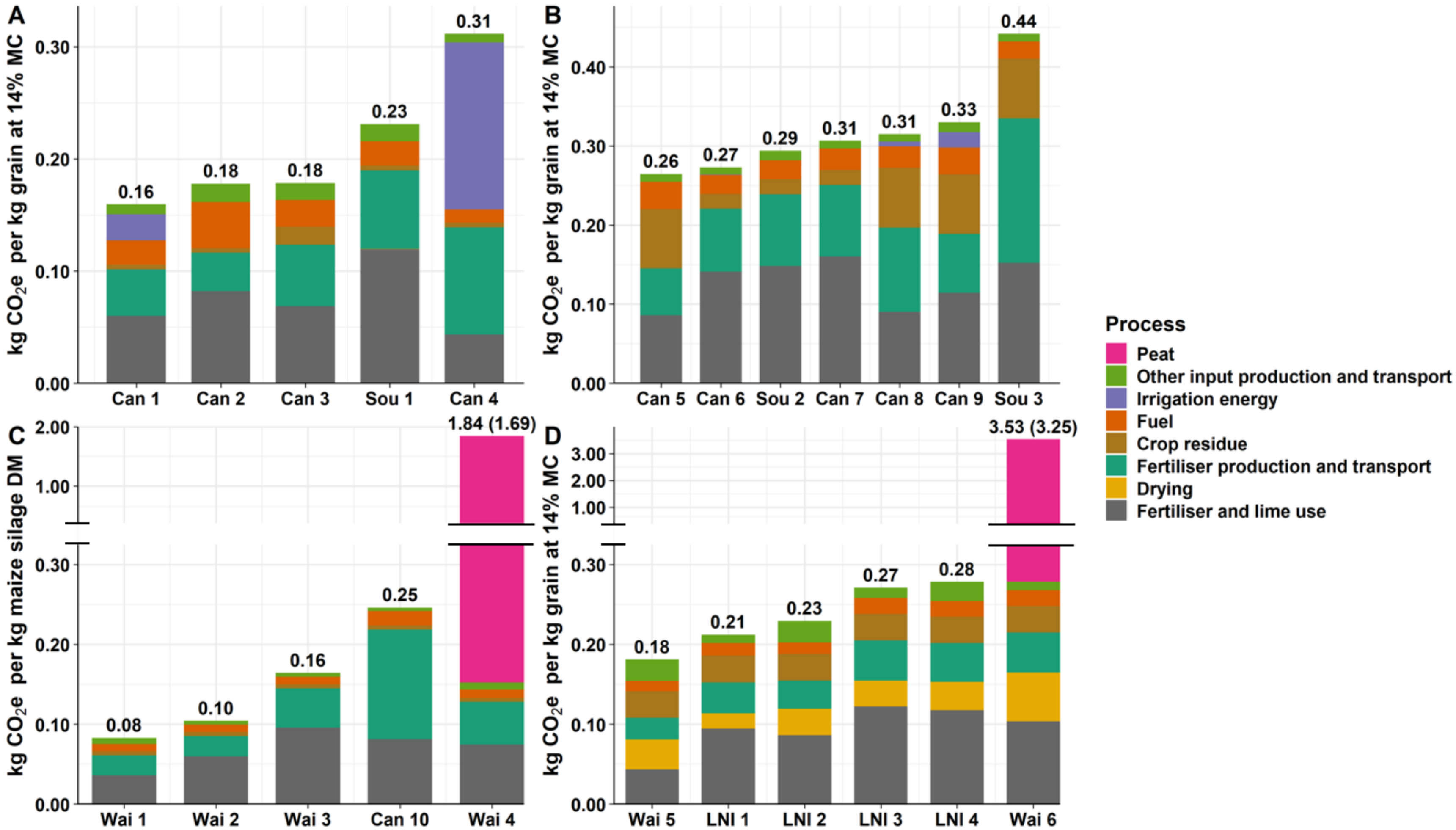

Figure 2. Farm-level carbon footprint by process contribution for (A) barley, (B) wheat, (C) maize silage, and (D) maize grain. Numbers above bars represent the emission factor for each farm, with peat-related emissions shown in parentheses. “Can” means farm is located in the Canterbury region, “Sou” in Southland, “Wai” in Waikato and “LNI” in the Lower North Island. "Fertiliser and lime use" represents the GHG emissions from in-field fertiliser and lime use. "Crop residue" represents emissions associated with above- and below-ground residue remaining after harvest, either incorporated, burned, baled. Economic allocation was applied for Can 1, 2, 4 and Sou 1 as they reported baling and selling straw. Can 5, 8, 9 and Sou 3 reported burning of crop residue. Other farms reported leaving crop residue in field. "Drying" accounts for the energy required to dry grain to 14% moisture content (MC). "Irrigation energy" accounts for the energy required to pump water, with Can 4 being the only farm having a diesel-powered irrigation system. "Fertiliser production and transport" includes the upstream emissions associated with manufacturing and transporting fertiliser inputs. "Other input production and transport" includes the production and transport of agrichemicals and seed. "Peat" represents emissions from drained peatland where two farms reported establishment on peat soils.

Presenting the data at farm level reveals both the average pattern and the heterogeneity in source contributions that is masked in aggregated results. Yields play a large role in determining the carbon footprints of feed crops. When excluding peat emissions, the lowest carbon footprints observed are in the highest yielding crops, maize silage (21.9 t DM/ha). However, the lowest yielding crop, barley (7.5 t grain 14%MC/ha), had smaller carbon footprints than wheat (9.2 t grain 14%MC /ha).

One key difference between wheat and barley systems relates to the management of crop residues. According to the survey, most barley producers (4 out of 5 surveyed) reported baling and selling straw. In these cases, economic allocation between grain and straw outputs was applied in accordance with guidelines from the International Dairy Federation (IDF, 2022).

In contrast, most wheat producers (4 out of 7 surveyed) reported burning crop residues in the field. This practice explains the relatively large share of emissions attributed to crop residue management in wheat systems. No wheat producers reported baling and selling straw; therefore, economic allocation between grain and straw was not applied, which contributes to the higher carbon footprint values observed for wheat.

Across all farms, emissions were typically dominated by fertiliser- and lime-related emissions (both upstream production and on-farm soil emissions), except those on peatland. This was followed by fuel and, where relevant, irrigation energy and drying. Drying emissions were the highest for maize grain given that commercial gas dryers are needed to dry the grain from 18-19% down to 14%. Irrigation energy per kg grain was the highest on the barley crops using diesel powered irrigation, but overall lower yields (7.5 t/ha for barley compared to 9.2 t/ha for wheat) would also explain the lower observed emissions. For example, one farm that was using diesel powered irrigation (second bar from the left in Figure 2) had 3 times higher irrigation-related emissions than the farm using electrically powered irrigation (first bar from the left in Figure 2).

3.2 National Weighted Average

There were not enough farms in each region for each crop to generate regional carbon footprints so national weighted average carbon footprints for each crop were calculated. This was achieved by apportioning each farm's carbon footprint on its contribution to the total yield from all farms for each crop following the formula:

$$\mu_w = \frac{\sum w_i \, x_i}{\sum w_i}$$

Where:

- x_i =farm EF (kg CO_2e/kg crop, on a DM basis for maize silage or 14% MC for grains)
- w_i =production volume (tonnes)
- μ_w =national weighted EF for given crop

To quantify variation around the mean, the production-weighted standard deviation (SD) was calculated. The weighted variance and SD are defined as:

$$\sigma_w^2 = \frac{\sum w_i \left(x_i - \mu_w\right)^2}{\sum w_i}$$

$$\sigma_w = \sqrt{\sigma_w^2}$$

Where:

- σ_w = weighed SD

This approach accounts for differences in production scale among observations, giving greater influence on farms with higher production.

3.2.1 Without peat

Firstly, the national EF per crop were calculated without any peat contribution (Figure 3). The lowest observed carbon footprint is for maize silage. Drying seems to be responsible for maize grain having a higher carbon footprint than barley. High fertiliser use and crop residue handling in wheat causes the highest carbon footprint out of the 4 studied crops.

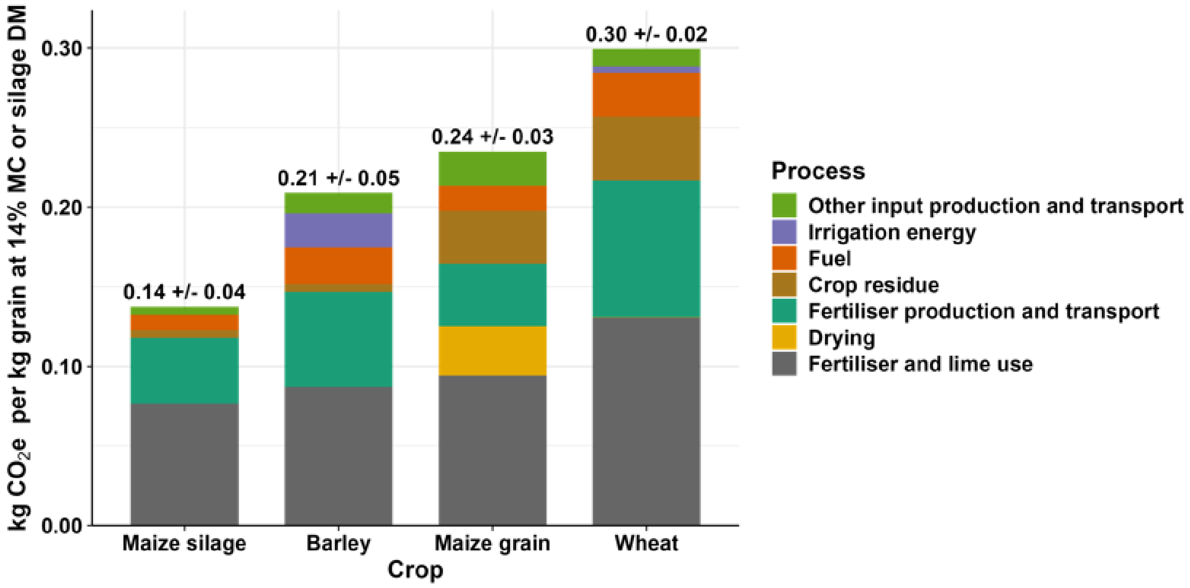

Figure 3. National weighted average carbon footprints for barley, wheat and maize grain. Numbers above bars represent the emission factor for each crop with weighet standard deviation (SD) Grains carbon footprints are reported on a 14% moisture content (MC) basis while maize silage carbon footprint is reported on a dry matter (DM) basis. "Fertiliser and lime use" represents the GHG emissions from in-field fertiliser and lime use. "Crop residue" represents emissions associated with above- and below-ground residue remaining after harvest, either incorporated, burned, baled. "Drying" accounts for the energy required to dry grain to 14% MC. "Irrigation energy" accounts for the energy required to pump water. "Fertiliser production and transport" includes the upstream emissions associated with manufacturing and transporting fertiliser inputs. "Other input production and transport" includes the production and transport of agrichemicals and seed.

Given the limited number of farms surveyed per crop and the geographic concentration of production in particular regions, it was not possible to generate statistically robust regional carbon footprints. Instead, production-weighted national average EFs were calculated for each crop, with greater influence given to farms with higher production volumes. This approach is consistent with standard practice in national-scale agricultural LCA studies where primary survey data are limited and ensures that the national EF reflects the actual composition of national supply rather than treating each farm as an equal observation. Using weighted SD reflects genuine variation in farm-level practice, which highlights the variations in fertiliser nitrogen rates, yield, and fuel use, rather than measurement uncertainty, and should be interpreted accordingly.

Comparing these results to previously published NZ estimates provide a useful validation check. The maize silage EF of 0.14 kg CO_2e/kg DM is consistent with the prior estimate of 0.19 kg CO_2e/kg DM, suggesting the survey sample may be representative of the national maize silage industry despite the small sample size (Ledgard & Falconer, 2015). This is also within the range reported by Lombardi et al. (2024), where modelled maize silage carbon footprints ranged from 0.18–0.20 kg CO_2e/kg DM depending on the nutrient management scenario. Furthermore, the average yield measured in our sample, 20.8 t DM/ha, is smaller than the national average for the same year; 22 t DM/ha (FAR, 2025).

For the grain crops, direct comparison with previous reports on a DM basis rather than 14% MC is possible. Converting the prior barley estimate of 0.36 kg CO_2e/kg grain DM yields approximately ~0.31 kg CO_2e/kg grain 14% MC. This report puts barley carbon footprint ~30% lower than this previous estimate, likely reflecting improvements in nitrogen use efficiency and yield among surveyed farms in recent seasons. It needs to be mentioned that potential differences could also be caused by the absence of irrigation-related emissions in previous reports (Ledgard & Falconer, 2015).

Another more recent recorded carbon footprint of NZ barley seems to be closer than the one calculated in this work. Lombardi et al., (2024) reported a 0.17 kg CO_2e/kg grain for barley fertilised with inorganic input, which is in the range calculated here (0.21 ± 0.05 kg CO_2e/kg grain 14% MC).

For wheat, a carbon footprint of 0.17-0.20 kg CO_2e/kg grain 14% MC was reported by Lombardi et al. (2024). This is lower ~30% lower than the one reported here (0.30 ± 0.02 kg CO_2e/kg grain 14% MC). One key difference between the wheat carbon footprint is how crop residues is treated. In this work, most growers reported burning residues, whereas crop residue was assumed to be sold in the previous work.

The relatively wide weighted SD for barley (±0.05 kg CO_2e/kg grain) compared to the other crops reflects genuine heterogeneity in barley production systems across the sample, with meaningful variation in from diesel powered irrigation. The narrower SDs for wheat and maize grain suggest more homogeneous production practices within those samples, though the small sample sizes limit the strength of this interpretation.

When comparing results across studies, sample composition, location and methodological assumptions must be considered. For example, Lombardi et al. (2024) is based on a single case study while Ledgard & Falconer (2015) used a different survey year and much bigger sample size. These differences mean that direct numerical comparisons should be interpreted with caution, and observed divergences may reflect methodological differences as much as genuine changes in farm-level emissions performance.

3.2.2 Drained peatland emissions

As seen in the surveys and confirmed in the literature and industry experts, wheat and barley cultivation on peat is assumed to be negligible (Pers. com., FAR; MfE, 2025; Leathwick et al., 2002). Drained peatland emissions were attributed to maize silage and maize grain only, assuming 2.46% of cultivation is on drained peatland. As shown in Figure 4, this increases the carbon footprints of maize silage and maize grain to 0.315 kg CO_2e/kg grain 14% MC and 0.176 kg CO_2e/kg silage DM.

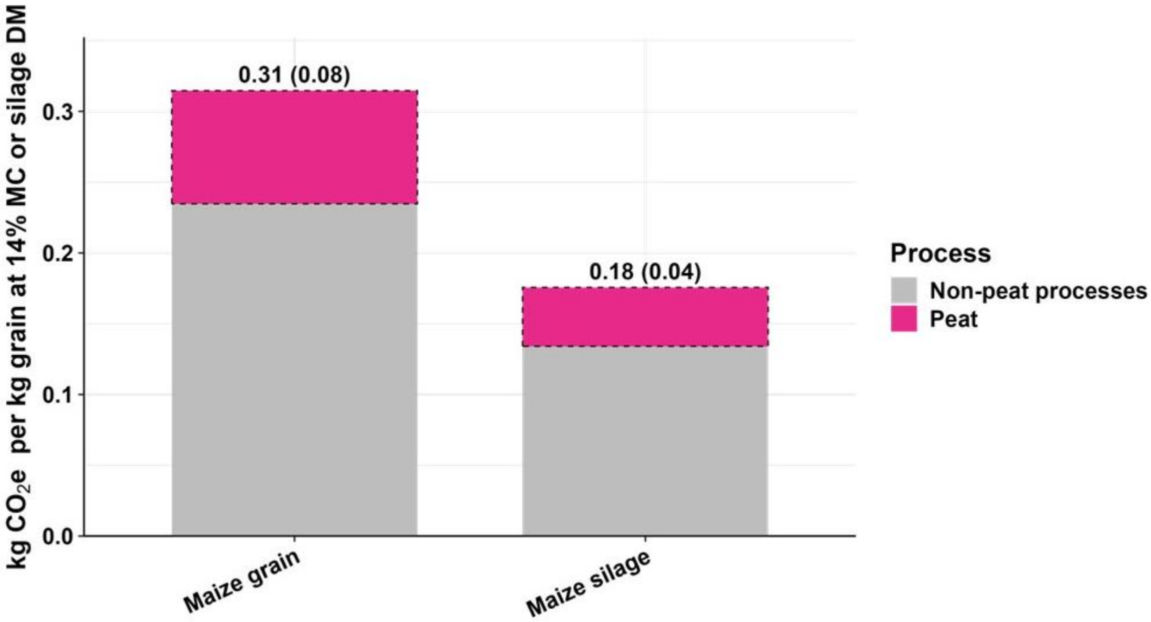

Figure 4. Peatland contribution to production-weighted average emissions for maize grain and silage. Numbers above bars are the weighed national averages with peat, with peat contribution in parentheses. Values are expressed per kg of 14% moisture content (MC) for maize grain and dry matter (DM) for maize silage. Results assume 2.46% of the cropping area is on drained peatland. Stacked bars show the non-peat baseline plus the modelled peat conversion to cropland contribution.

Peatland soils are a well-established source of CO_2, CH_4, and N_2O emissions when drained for agriculture, and their inclusion or exclusion from a national average EF can meaningfully affect the result depending on the prevalence of peat soils within a given crop's production area. The approach taken here follows a two-step logic: first establishing which crops might be grown on drained peatland, and second, quantifying the likely peat area attributable to each crop using national inventory data.

It is important to note that the peat attribution ratio used in this study represents a national average scenario rather than a farm-level observation. The 2.46% factor assumes that peat soils are distributed proportionally across maize and other non-wheat, non-barley annual crops. This is a conservative assumption given that the Waikato's peat prevalence could be closer to 7-8% of cultivated land (Dresser et al., 2012).

The peat prevalence factor of 2.46% represents the best estimate achievable given currently available national data. Ideally, crop-specific peat soil coverage would be derived from a dedicated survey capturing soil type alongside production area and yield for each crop, data that do not currently exist in NZ at the national scale. In the absence of such data, the NZ GHG Inventory organic soil area under annual cropland (MfE, 2024) combined with the StatsNZ total annual cropland area (StatsNZ, 2025) provides the most authoritative and transparent basis for this estimate. Interestingly, the results gathered by the survey are below the estimates from the national values, as the reported area under drained peatland are 0.8% for maize silage and 2% for maize grain.

Should future surveys collect crop-specific peatland coverage data, the peat prevalence factor and associated EF adjustment could be refined considerably. In the interim, the approach adopted here is consistent with the precautionary principle: peat emissions are neither ignored nor overstated but estimated transparently from national inventory data with the underlying assumptions clearly documented so that the calculation can be updated as better data become available.

4. Sensitivity Analysis for Barley Grain

Figure 5 presents the carbon footprint of barley grain under four different allocation approaches. In the no-allocation scenario, the functional unit encompasses both grain and straw (1 kg grain + 0.76 kg straw), yielding a footprint of 0.268 kg CO_2e/kg grain at 14% MC.

When allocation is applied to isolate the grain-only footprint, the result is reduced substantially across all three methods: energy (metabolisable energy; ME) allocation yields 0.171 kg CO_2e/kg grain at 14% MC, economic allocation 0.187 kg CO_2e/kg grain at 14% MC, and biophysical (N content) allocation 0.199 kg CO_2e/kg grain at 14% MC, showing reductions of 36%, 30%, and 26% respectively relative to the no-allocation result.

The spread across allocation methods is modest in absolute terms (0.028 kg CO_2e/kg grain between the lowest and highest allocated results), suggesting that the choice of allocation approach is not a dominant source of uncertainty for barley grain.

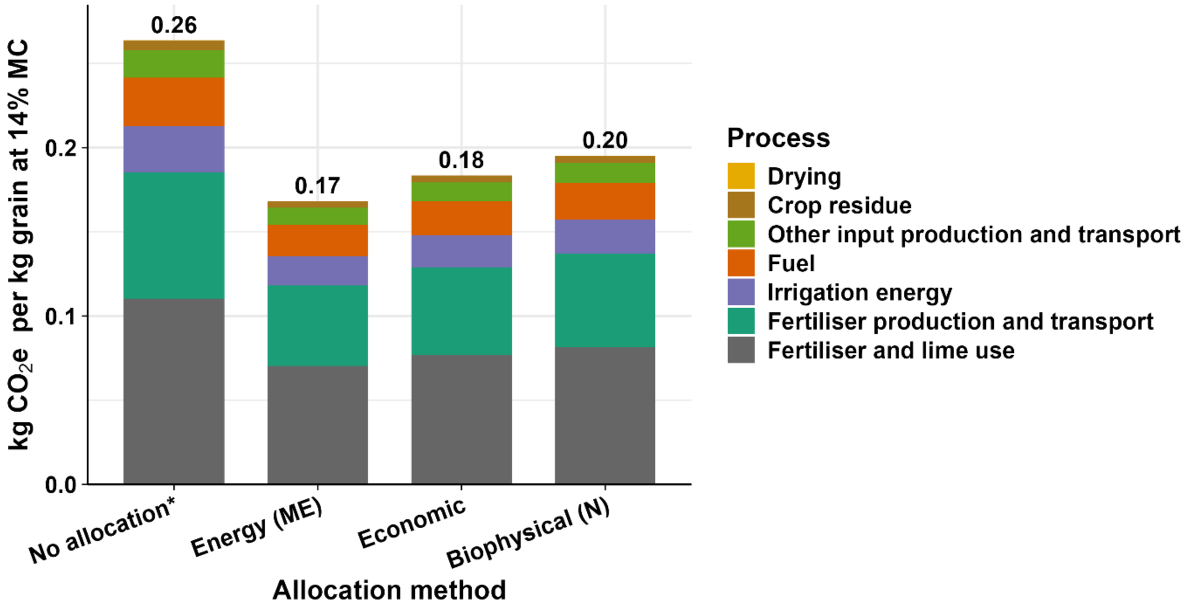

Figure 5. Barley allocation sensitivity analysis. Stacked bars show the production-weighted contribution of each process to the barley carbon footprint for 1kg of grain at 14% moisture content (MC). Four scenarios were analysed: Metabolizable energy (ME), Economic, Biophysical (N-content) and No allocation. (*) For the No allocation case, emissions from 1 kg grain and 0.76 kg of harvested straw are presented. Numbers above bars are total footprint values.

The economic allocation result of 0.187 kg CO_2e/kg grain is recommended as the primary reported value and is the one that was used when farms reported baling and selling straw as a by-product. The selection of an appropriate allocation method for co-products is a recognised source of methodological variation in feed ingredient LCA, and international guidelines offer complementary but not fully consistent guidance. Where wheat grain is produced for dairy feed, the International Dairy Federation (IDF, 2022) recommends economic allocation as the default approach, a position also adopted in the first edition of the FAO LEAP Guidelines for Livestock Feed (FAO, 2016).

For dairy feed specifically, where the functional purpose of the ingredient is energy supply to the animal, energy allocation has a strong biophysical rationale. The N-based biophysical allocation is less appropriate for an energy-dense ingredient such as wheat grain, where protein is a secondary rather than primary function, and is included here for completeness.

It should be noted that, where straw is combusted or left in field rather than used as livestock feed or bedding, all emissions are attributed to the grain functional unit in full under a no-allocation approach. When straw generates no economic or nutritional co-product value, all burden falls on the grain only. This further reduces the appropriateness of the no-allocation scenario as a primary reported value and strengthens the case for applying co-product allocation in all contexts where straw has a defined end use.

5. Conclusion

This study delivers the first comprehensive, primary-data-based update to the carbon footprints of NZ's four major livestock feed crops in over a decade. The results provide timely and credible emissions factors that can be applied by arable producers, pastoral farmers, processors, and their advisors in scope 3 reporting and farm-level emissions accounting.

The national weighted average emissions factors reported here reflect genuine variation in farm practice rather than measurement uncertainty. The variation in results across farms is most pronounced for barley, where diesel-powered irrigation and variable yields introduce significant heterogeneity. This farm-level assessment could help individual producers to reduce their footprint through targeted interventions, particularly around fertiliser nitrogen management, irrigation efficiency, and residue handling.

Crop residue management, and particularly the widespread practice of burning wheat stubble, emerges as an important lever for emissions reduction. Unlike the decay of incorporated residues, burning generates net anthropogenic CH_4 and N_2O emissions while simultaneously precluding the economic allocation of emissions to a straw co-product. Transitioning burned residues to incorporation or baling would reduce wheat footprints and improve comparability with barley systems.

Where economic allocation was applied, the choice of allocation method, whether based on revenue, nitrogen content, or energy content, had only a modest effect on the resulting emissions factors. This provides some reassurance that the reported values are robust to methodological differences in how co-product emissions are distributed and supports their use as default values across a range of LCA frameworks.

The emissions factors presented in this report are suitable for immediate use as NZ-specific default values in life cycle assessments of pastoral agriculture products. As the sector's emissions measurement infrastructure matures and survey coverage expands, these factors should be revisited on a regular basis to capture ongoing changes in cropping practice, input use efficiency, and regional production mix.

6. Limitations

The primary limitation of this study is the small sample size. The number of farms surveyed for each crop type is modest, and the degree to which these farms are representative of national production patterns cannot be fully verified. While farms were selected to span key producing regions and a range of management practices, the sample was not drawn from a formal sampling frame, and results should be interpreted accordingly. The modest reductions observed for grain crops relative to earlier benchmarks may reflect genuine productivity and efficiency gains across the arable sector, but given the small sample, it is equally possible that this convergence is coincidental rather than indicative of a sector-wide trend.

The treatment of drained peatland emissions represents one of the more significant sources of uncertainty in the national averages for maize. The 2.46% peat prevalence factor used here is a conservative estimate derived from national inventory data. Ground-level evidence from the Waikato suggests that the true proportion of maize grown on peat could be considerably higher (7–8% of cultivated land). Future survey work that captures soil type alongside production area and yield would allow this factor to be refined and the national emissions factor for maize to be reported with greater confidence.

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