THE CLIMATE SOURCE

A case study on cradle-to-gate Product Carbon Footprints in the dairy sector

Emissions inventory accounting and project integration for small and medium-scale dairy processors

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The Climate Source *develops market-based strategies for agricultural systems change. We are leading experts in carbon accounting, supply chain programs, and co-financing strategies.*

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Executive Summary

Accounting Methodology and Case Study for Embedded Emissions

The Climate Source partnered with Idaho Milk Products (IMP) to pilot a cradle-to-facility gate carbon accounting methodology designed to improve data-sharing mechanisms and incentivize GHG reductions across the value chain. Our goal was to demonstrate the feasibility of embedding material, transport, and processing energy emissions into product-level inventories. In doing so, we aimed to prove that our BoundDairy Accounting tool enables cooperatives and processors to attribute emissions to customers, while avoiding double counting, free ridership, and inaccurate inventories that results from the inherent complexities of varying baseline and boundary assumptions.

The physical allocation model establishes clear economic boundaries while dynamically allocating emissions from supplier farms, transportation routes, and processing facilities into product carbon footprints. The methodology:

- **Improves accuracy and comparability** through supplier-specific data and allocation logic
- **Reduces redundancies** in reporting to both customers and regulatory systems
- **Credibly differentiates** low-carbon ingredients linked to on-farm practices
- **Lowers the risk of double counting** and inconsistent attribution
- **Increases customer retention** through transparent and verified emission reductions

This study evaluates how activity-based data sources and allocation methodology streamlines reporting, improves data accuracy, and drives sustainability investments. By following the proportion of raw milk distributed to dairy ingredients, processing flows, and product relationships, the model ensures that mitigation efforts at the farm level are accurately reflected in a product carbon footprint (PCF). Data quality standards and allocation mapping provide guidance for designing an accounting system for reliable carbon crediting and reporting to downstream customers.

We performed sensitivity and uncertainty analyses in order to determine that the model responds to on-farm changes to butterfat and protein components in the PCF outcomes. The additional functionality and higher data and calculation requirements, coupled with physical allocation, deliver differentiated PCF values and overcome the risks of double counting, free ridership, and inaccurate inventories.

Data collection and component traceability can be improved, and cooperatives and processors are best positioned to drive those changes. Advancements in project-inventory integration, supply chain emissions transfer methodology, and verification standards will enhance the business case for all dairy stakeholders.

Dairy GHG Reporting Landscape

The livestock sector, particularly dairy, is a significant contributor to global greenhouse gas (GHG) emissions, accounting for approximately 14-19% of total emissions (Blaustein 2023). Additionally, shared value chain emissions, particularly from raw milk production, account for the largest share of food companies' carbon footprints at 70-95% (Siegl et al. 2023). While reduction of dairy GHG emissions aligns with global net-zero pathways, achieving meaningful reductions requires well-defined strategies, robust data structures, and standardized methodologies for emissions accounting.

GHG Protocol (GHGP) and the Science-Based Targets Initiatives (SBTi) set out to define the rules for measuring, reporting, verifying, and claiming GHG mitigation in agricultural supply chains. These frameworks are designed to standardize the approach for all of global agriculture and create a unified approach to GHG disclosure requirements. GHGP and SBTi typically engage consumer packaged goods companies. However, sustainability practitioners face numerous challenges when operationalizing current GHG reduction frameworks in the dairy sector, particularly around fair and credible attribution of reductions. Food companies and investors are concerned about double counting, free ridership, and claims assurance. Additionally, cooperatives and processors are required to report on GHG performance to multiple buyers who each have their own approach for measuring, reporting, and verifying emissions.

With limited resources both in time and technology, sustainability teams in the middle of the supply chain are overly burdened with reporting requirements–especially when buyers have different spatial and temporal boundaries, baselines, fiscal years, and investment approaches. The divergence from a standardized, systematic strategy causes many dairy suppliers to spend an excessive amount of time providing data to a variety of platforms with little to no feedback on their performance. Because of inaccurate accounting and reporting burdens, the industry struggles to define the business case for GHG reductions. The future success of market-based initiatives to mitigate climate change is dependent on cooperatives and processors having the right tools and capabilities to measure, control, and manage carbon assets and attribute them to the product supply chains they manage.

What's at Stake

The risks associated with dairy supply chain accounting are impacting the business case for farms, cooperatives & processors, buyers, and retailers to participate in carbon mitigation efforts. Additionally, the investment case for on-farm reductions depends on the ability to make credible claims, which relies on robust and accurate accounting processes.

Supply chains are dynamic, interactive, and complex. The accounting system must reflect dairy operations and, ideally, enable market development for low carbon dairy ingredients.

Operationalizing GHG Reductions in Dairy Value Chains

One promising approach is the calculation of Product Carbon Footprints (PCFs), a cradle-to-gate measure of emissions associated with a specific product, using physical allocation methodology. PCFs enable value chain actors to quantify, compare, and reduce emissions at the product level rather than relying solely on company or facility-wide averages. Additionally, tying PCFs to customer-specific investments ensures that the emissions intensity of a product reflects the level of support or intervention provided by each buyer. This approach diverges from traditional allocation mechanisms, such as market-share or conventional mass balance accounting, which distributes reductions based on volume or financial stake regardless of who funded the GHG reduction effort.

This BoundDairy Accounting pilot was designed to help address the need for a more rigorous, scalable, and accurate approach to product- and farm -level carbon accounting in the dairy sector by calculating PCFs using a physical allocation methodology. In partnership with Idaho Milk Producers (IMP), the pilot aimed to:

- **Obtain product-level carbon data**, using primary farm- and plant-level inputs wherever possible, rather than relying on industry averages or estimates.
- **Standardize allocation across products** using a transparent, auditable methodology developed by The Climate Source. Inspired by principles of the E-Ledgers Institute, this methodology ensures emissions are physically allocated and follow the flow of materials and energy from cradle-to-gate.
- **Develop an integrated tool that links** currently fragmented datasets (e.g.product specifications, milk supply, transportation) into a coherent, dynamic accounting model that supports emissions tracking and project attribution.

Introduction

At **Idaho Milk Products** (IMP), rising expectations from customers and farmer members collided with evolving emissions reporting requirements. With a clear mission to craft the world's finest dairy ingredients while protecting the environment, Director of Sustainability Jeremy Pike found IMP's emissions data fragmented – spanning farm-level reporting like FARM Environmental Stewardship (FARM ES) and U.S. Dairy Stewardship Commitment to corporate pledges like the SBTi and upcoming Life Cycle Assessment (LCA) work.

In 2024, IMP published a Sustainability Insights Report outlining food safety, mindful water use, energy efficiency, and emissions inventory by source – including on-farm footprint from FARM ES version 2. This allows IMP to share emissions with buyers using fat-and-protein-corrected milk. Yet, customers often require product-specific footprints tailored to their own methodologies – ranging from spend-based estimates to conversion equations using national averages. The result? Disconnected data and unclear links between farm practices and buyer reduction targets.

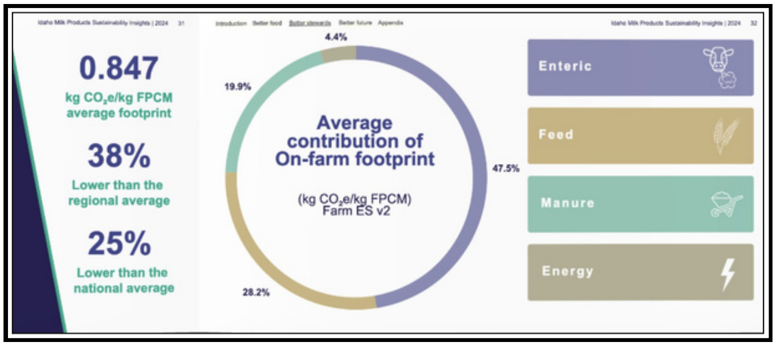


Figure 1: Idaho Milk Products Sustainability Insights

"We are doing a lot of counting, but we are not accounting"

Jessie Deelo, CEO of **The Climate Source** and the founder of BoundDairy Accounting, has been working across the dairy value chain leading investment strategies for dairy buyers, building low-carbon sourcing strategies, and advocating for the premiumization of low-carbon dairy ingredients. She acts as the sustainability expert for the Center of Excellence with the American Dairy Products Institute (ADPI), where she met Jeremy Pike and the CEO of Idaho Milk Products, Daragh Maccabee. At the ADPI Annual Meeting in Spring of 2024, Jessie sat down with Jeremy and Daragh to discuss why dairy cooperatives and processors struggle to find the business case for GHG reductions. "We are doing a lot of counting, but not *accounting.*" Jeremy and Daragh knew from experience that the need for innovation is imperative to the industry's success. Together, they set out to develop an accounting system that would enable the profitable, scalable, and sustainable growth of low-carbon dairy ingredient markets.

Around this same time, the **E-Ledgers Institute** (ELI) founders, Robert Kaplan of Harvard University and Karthik Ramanna of Oxford University, published a series of articles in Harvard Business Review describing their accounting concept of embedding emissions in products and passing them through the supply chain. Jessie joined the Technical Committee during the development of ELI's guiding principles for their proto-standard and worked with Bob Kaplan to inform the principles and practices of the BoundDairy methodology.

Aligning Dairy Supply Chain Operations and Activities with Carbon Footprint Guidelines

BoundDairy's GHG accounting and allocation methodology follows a structured approach based on PACT Pathfinder Framework (Partnership for Carbon Transparency, World Business Council for Sustainable Development 2023), which is backed by ISO and GHG Protocol standards. Specifically:

1. Physical allocation is always necessary for multi-output facilities*: Only when a facility produces a single output can we avoid allocation of GHG emissions, as all emissions are directly linked to the single product. In such cases, we assess if subdivision is possible and disaggregate common processes that produce a single end product. Physical allocation is therefore unavoidable in multi-output facilities, as emissions cannot be wholly assigned to a single product.*

2. Prioritize product category rules and sector-specific guidance: *The IDF Global Carbon Footprint Standard for the Dairy Sector is used to apply physical allocation when subdivision isn't feasible, using milk solids content to allocate emissions (The International Dairy Federation 2022).*

3. Select the most suitable allocation method: *Milk solids content reflects the causal relationship between products and pre-processing emissions associated with raw milk. Various methods can be evaluated across the value chain, ensuring the following:*

- *Reflection of causality between outputs and emissions*
- *Provision of accurate and credible estimates*
- *Support of GHG reduction and decision-making*
- *Adherence to GHG Protocol*

Additionally, BoundDairy's consistency with the E-Ledger Institute's E-Liability Proto-Standard ensures that its carbon accounting methodology also adheres to these critical principles:

- ***Direct Emissions Recording:*** *The tool ensures that all material, direct GHG emissions are recorded by the entity responsible for them, whether through direct measurement or calculation. This is consistent with E-Liability Principle 1.*

- ***Verification of Emissions****: All emissions records in BoundDairy, whether direct or embedded, are verified to the reasonableness standard through quantification tools or third-party audits, aligning with Principles 2, 4, 6, and 9. A limited assurance audit on the methodology and third-party verification of the outputs will be performed.*

- ***Causal Allocation****: All emissions recorded under BoundDairy are allocated to the entity's outputs from the current or historic period, maintaining a causal logic. This ensures the emissions are properly linked to the production processes, as per Principles 7 and 8. The ability to forecast future periods is still being developed.*

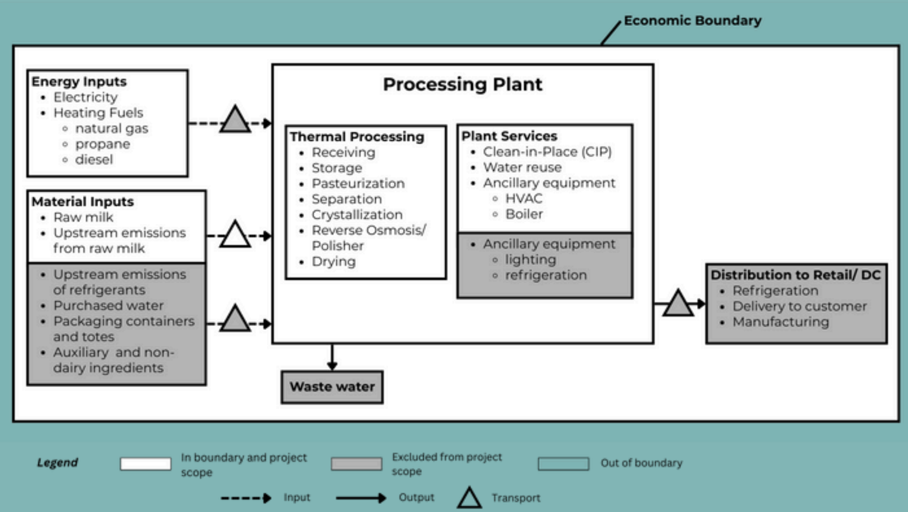
Built to Scale with Evolving Data Structures and Customer Programs

Our approach builds upon LCA data processes and methodologies with a priority on primary data and cut-off methods when activities fall outside an operation's economic boundary. For IMP, the economic boundary includes activities displayed in Figure 2.

Both traditional dairy inventory accounting approaches and the BoundDairy Accounting approach aim to identify hotspots, prioritize intervention decisions, and support sustainable product design. Both methods also quantify environmental impacts across processing stages in relation to product function. However, their structure, scope, and decision-making utility differ significantly. Traditional dairy inventory accounting approaches focus on building credible company-level emissions footprints for disclosure purposes. Meanwhile, BoundDairy's PCF approach aims to build primary data-driven systems that enable allocation of emissions to products and customers, including ongoing attribution of emissions reduction projects to investors.

Overall, integrating traditional LCA approaches and high quality, high granularity emissions data, the **BoundDairy Accounting system builds a facility-based emissions inventory and allocation tool that addresses the dynamic realities of customer-specific demands, commercial relations, evolving product mixes, supply chain dynamics, and decarbonization investments.**

IMP is well-positioned to lead in this space with its vertically integrated structure and streamlined decision-making, allowing for rapid deployment of GHG-reduction strategies and transparent customer engagement. While the path to a low-carbon value chain may be more complex for larger processors, the foundation lies in operational clarity, direct supplier relationships, and the ability to attribute reductions to specific farm volumes and practices.



Critical Importance of Economic Boundaries

An entity includes only the emissions within their operational control, including purchased materials and energy. Strict economic boundaries ensure the transferability of emissions to downstream customers based on purchased product volumes and specifications. This avoids double counting, free ridership, and issues with baselines and temporal and spatial boundairy variance.

Figure 2: Adapted from Input and output flow diagram for fluid milk processing, packaging, and distribution (Nutter 2013)

Standardizing and Improving Data Quality and Granularity

Onboarding began by identifying existing datasets (e.g., processing flows, plant layouts, accounting records, transportation logs) and mapping them into a format that supports evolving emission factors and operational changes. Data templates were customized to integrate supplier-specific volumes and product attributes, enabling clear links between inputs and downstream emissions. This setup ensures a structured baseline for downstream analyses, including recalculations, scenario modeling, and sensitivity testing.

Improving data granularity and the ability to enhance primary data over time allows dairy processors like IMP to leverage existing data sources and establish prioritization criteria for on-farm GHG projects. This not only supports strategic planning but differentiates the processor by increasing transparency and building trust with downstream buyers. Customers are more likely to rely on cradle-to-gate emission factors derived from verified data, rather than the patchwork of estimation methods currently in use.

Table 1: Data Sources by Emissions Source

Emission Source	Description	Primary Data	Secondary Data
Milk Supply	• **Farm-level milk supply data** (volume, fat %, protein %) is converted to FPCM using IDF's conversion equation. • **Farm-level emission factors** (CO_2e / FPCM) are then applied. • Total emissions are calculated by multiplying the standardized volume by the emission factor for each farm-to-plant record.	Farm-level emissions factors (when available), Farm-level milk supply	Cooperative weighted emission factors (members without a baseline), US-based LCA cradle-to-farm gate results (external producers)
Ingredients	• Additional **plant-level inputs or transfers to internal plants** are accounted for by storing ingredient types and quantities. • Incoming dairy ingredients adopt a national cradle-to-gate LCA factor. • Incoming non-dairy ingredients require further assessment on materiality. • Emissions associated with transferred raw milk or dairy ingredients are allocated and excluded from the plant's inventory.	Quantity of incoming and outgoing dairy ingredients	National cradle-to-gate emissions factors

Table 1: Data Sources by Emissions Source, continued

Emission Source	Description	Primary Data	Secondary Data
Storage	• **Plant-to-warehouse** transport and energy consumption are collected at a product-level based on the share of storage volume dedicated to each product. • **On-site storage** space that utilizes heating or cooling is subdivided from the total energy consumption for specific product lines.	Monthly utility bills by energy source, Storage volume per product, Distance (miles)	US heavy-duty vehicle emission factor, State-grid emissions factor (electricity), US-based refrigerant GWP 100-year
Transportation	• **Farm-to-plant** routes or route groups are stored with truck capacity, distance and vehicle type. • This method accommodates processors with exact distances or limited route control. • Total emissions are calculated by multiplying the weight by the distance by the vehicle-level emission factor.	Total mass (short tons), Distance (miles)	US heavy-duty vehicle emission factor, OpenRouteService (ORS) optimized distances based on latitude/ longitude coordinates
Processing	• **Plant-level energy consumption** is collected and assessed for energy source, equipment type, output groups, and processing capacity. • The share of energy used for each activity is estimated and multiplied by the state-specific energy source's emission factor. • **Product-level emissions** are calculated by the product sum of each activity's emissions and respective share of product output.	Monthly utility bills by energy source	State-grid emissions factor (electricity), US emission factors (thermal energy)

Process Notes:

- *Supply and transportation emissions are allocated based on milk solids content*
- *Processing emissions are based on each output group's (e.g. butterfat-, protein-driven) energy consumption*
- *Total product emissions are determined by multiplying allocation factors by the total emissions for each source and time period*
- *Emission factors are calculated by dividing the total product emissions by the output quantity in a given time period.*

Allocation Mapping Ensures Accurate Inventories

In Figure 3, we illustrate how milk from two farms with different emissions intensities, measured in fat- and protein-corrected milk (FPCM) for comparability, and varying milk solids outputs can be allocated downstream, while maintaining inventories and avoiding double counting.

> **Fat- and Protein-Corrected Milk** is a standardized measure to calculate milk volumes based on fat, protein, and lactose using a common unit that is relevant to ingredient volumes and GHG emissions metrics.

As farm milk (left panel) moves through the primary processing phase (middle panel), milk from multiple farms is blended and dairy components (e.g. fat, protein, lactose) are separated. While operators do not have batch-level milk traceability, they do track solids quantities coming from each farm, since premiums are paid for solids contents. Emissions are allocated to these components following International Dairy Federation (IDF 2022) guidelines.

The facility inventory (right panel) demonstrates how milk solid emissions are allocated to buyers based on product quantities and specifications. Processors with data traceability can track the quantity of milk solids going to each product as well as the quantity of each product purchased by buyers. This information enables a physical allocation methodology where farm, transport, and processing emissions move through the value chain attached to milk solids and applied to products. As a result, processors can credibly report to customers the carbon footprints of their purchased product volumes.

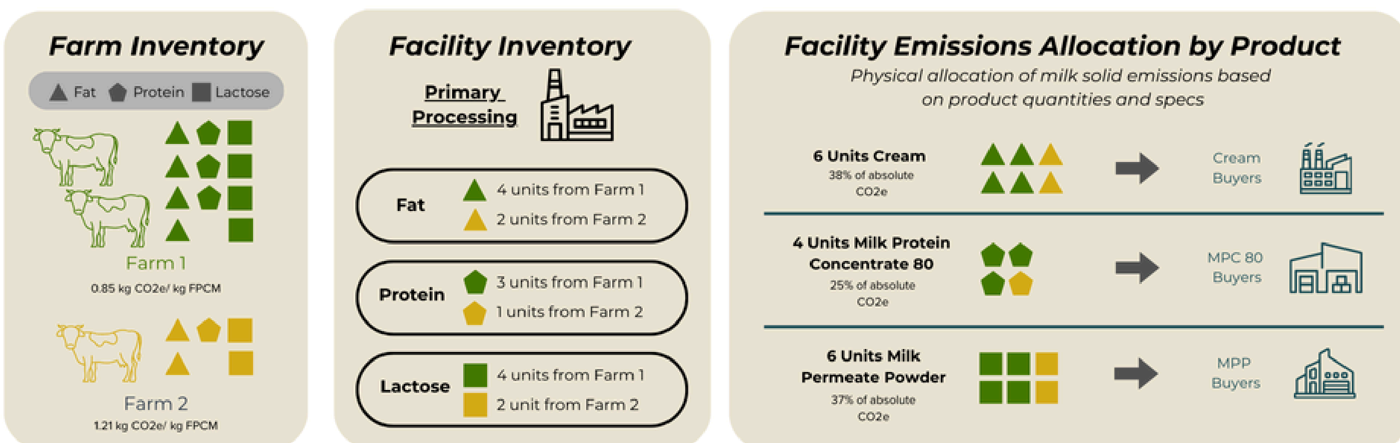


Figure 3: Physical allocation from farm gate through first processing

Assessing Emissions Correlation with Milk Solids Distribution

At the plant level, we assessed whether incoming milk volumes align with product output quantities. Integrity checks are performed to ensure that all emission sources are accounted for before and after allocation. We analyzed the correlation between emissions distribution and product relationships, particularly due to milk solid allocation. A few checks from the plant dashboard included:

- Increases in butterfat and protein components should correlate with increased product efficiency and lower product carbon footprints
- Product share of emissions should correlate to the milk solid distribution and coproduct relationships
- Total farm emissions must equal the sum of product's on-farm emissions after allocation
- Total transport emissions must equal the sum of product's transport emissions after allocation

Results

Enabling Supplier-Led Product-Level Emissions Reporting

The product carbon footprint outcome provides a breakdown of the total emissions inventory by source and reporting period. This includes data quality indicators, product quantities, and emissions intensity by product weight. Additional reports allow differentiation of the PCF by project and customer, aligning with business priorities and goals. Farm-level emissions are the dominant contributor, followed by processing and transportation, while storage emissions depend on the product type.

The product dashboard demonstrates how product quantity, specifications, and relationships all play a significant role in a product's carbon footprint results for a plant. Product categories and components can also show how dairy components are distributed to coproducts. The total emission share of each component should remain the same if new product specifications are added. The dashboard can identify discrepancies in underlying data or assumptions. The product dashboard also demonstrates how a distinct volume of raw milk will impact Milk Protein Concentrate 80 (MPC 80) differently than Milk Protein Permeate (MPP) due to varying milk solids content specifications and component distribution. A scenario analysis comparing seasonal variation can support project-to-product assignments as well as remaining quantity reserves for future opportunities. Additionally, transitioning from annual to monthly reporting intervals further supports dynamic modeling and increases the operational integration of the system.

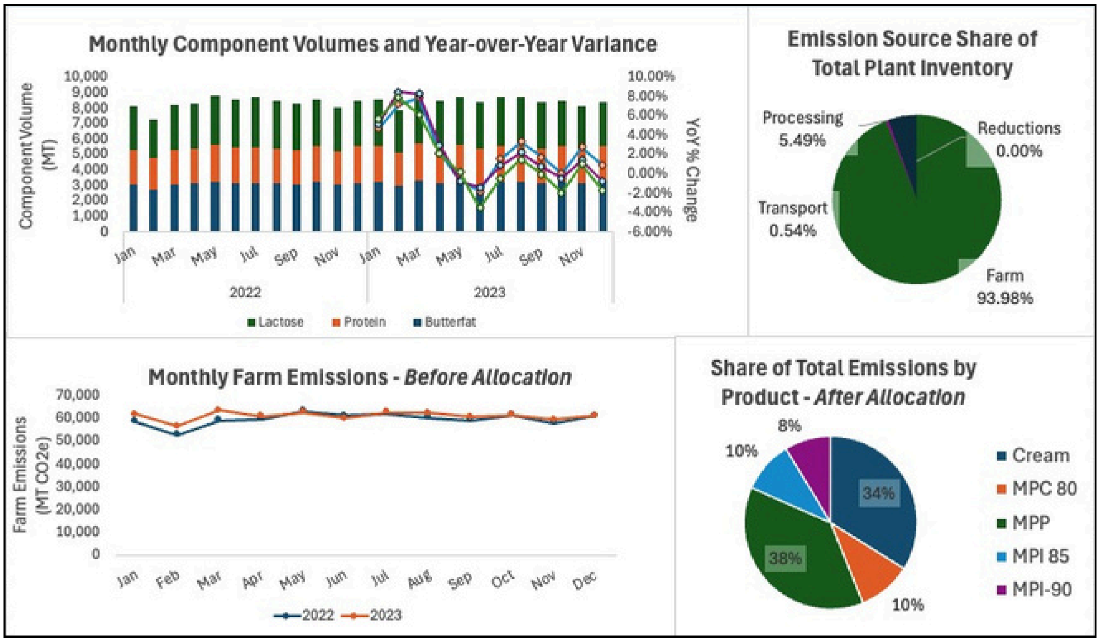


Figure 4: BoundDairy Plant Dashboard for IMP

In the above dashboard view, the *Share of Total Emissions by Product - After Allocation* shows that all of the milk volumes and emissions are allocated to the total volume of products during the reporting period. Applying physical allocation methodology from farm through processing-gate enables IMP to report supplier-provided product-level emissions.

Actionable Insights Streamline Reporting and Enable Differentiation

With one of the long-term objectives being improved investment confidence, a comparison view is explored to promote regional and product benchmarks compared to the previous national cradle-to-gate LCA published in 2012 (Thoma 2013) and the Net Zero Dairy Business Case (Clay 2022). A summary of emission intensities by stage reveals significant differences across various sourcing regions and product mixes. Farm-level emissions are the dominant contributor, followed by processing and transportation, while storage emissions depend on the product type.

Component	IMP (2023)
Butterfat	3.47 kg CO2e/ kg Product
Protein	6.77 kg CO2e/ kg Product
Lactose	6.91 kg CO2e/ kg Product
Average	**5.15 kg CO2e/ kg Product**

Table 2: Cradle-to-gate Emission Intensity by Stage

Stage	IMP (2023)
Farm	4.84 kg CO2e/ kg of Product
Transport	0.03 kg CO2e/ kg of Product
Processing	0.28 kg CO2e/ kg of Product
Total	**5.15 kg CO2e/ kg Product**

Table 3: Average Cradle-to-gate Emissions Intensity by Component

BoundDairy Accounting captures contextual attributes within emissions inventories, such as primary data share, time range, and product mix. While farm-level emissions data is relatively well-documented, processing and transportation activities have significant data gaps. Additionally, while IMP exemplifies a 100% sampling rate, primary data for another cooperative may represent only 9% of total emissions, as shown in Figure 5. While data improvement is important, balancing it with feasible outcomes is crucial, as extensive efforts to refine assumptions in processing and transport can divert resources away from more impactful farm-level investments.

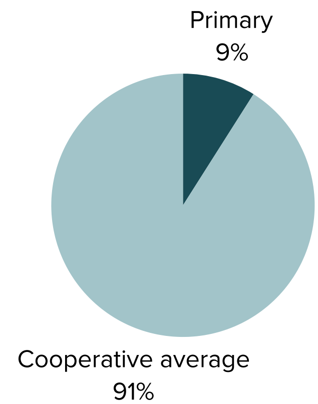


Figure 5: Primary Data Share of Farm Emissions

Given the additional functionality of the BoundDairy Accounting system, it has higher data and calculation requirements to reflect the real-world complexity of dairy processing, where raw milk is simultaneously transformed into multiple co-products.

Product Carbon Footprint Results

Dairy cooperatives and processors manage diverse product mixes across facilities, transferring dairy inputs internally or purchasing externally. To ensure accurate carbon accounting, these transactions are assessed using the subdivision or cut-off method, as outlined in the GHG Protocol Scope 3 Standard. Idaho Milk Products uniquely uses butterfat, protein, and lactose in its final products with little to no transfers with external plants. Protein demand drives the distribution of these components, valorizing the remaining butterfat and lactose into Cream and Milk Protein Permeate, respectively.

The product carbon footprint depends on two key elements 1) the milk solid content specifications for each end product and 2) how each separated component is distributed across its ingredient outputs. Different product specifications require different amounts or raw milk, for example, producing MPI 90 requires more raw milk per kg of product than MPC 80, so more on-farm emissions are allocated to MPI 90. Allocation of on-farm emissions therefore depends on both supply and demand. For example, if more of the available protein from raw milk is distributed to MPC 80, that shift will change the distribution of protein across the product portfolio and may lower or raise the plant's average PCF. Processors can link product outputs to raw milk proportions using the distribution share to improve decision making across the value chain.

Table 4: Product Simple Example

Product	Component	Milk Solid %	Quantity MT	PCF kg CO2e/ kg Product
Cream	Butterfat	50%	76,247	3.43
MPC 80%	Protein	94%	34,739	6.63
Permeate	Lactose	97%	42,420	6.79
Total			**153,406**	**5.09**

Table 5: Product Co-product Example

Product	Component	Milk Solid %	Quantity MT	PCF kg CO2e/ kg Product
Cream	Butterfat	50%	76,247	3.47
MPC 80%	Protein	94%	11,580	6.70
MPI 85%	Protein	97%	10,898	6.89
MPI 90%	Protein	99%	10,293	7.01
Permeate	Lactose	97%	42,420	6.86
Total			**151,439**	**5.15**

Milk Solid indicates the total fat, protein, and lactose for each product. With a single protein-derived product, all of the skimmed milk is distributed to the MPC 80%, meaning more MPC 80% is processed in the Simple example (Table 4) than in the Co-product example (Table 5).

When multiple protein-derived products are processed at a given plant, less MPC 80% is processed, impacting the overall milk solid distribution and product carbon footprint.

[5] *Since fat- and lactose-derived products still contain trace amounts of protein due to the separation process. The total quantity and Product Carbon Footprint (PCF) differs by about 1.2% between a simple allocation and a co-product allocation as a result of the balancing process.*

Sensitivity Analysis

To understand the robustness of our methodology for dairy ingredient product carbon footprint, we conducted a sensitivity analysis that tested how changes in key variables impacted both overall emissions and product-specific results. Variables were selected based on their relative contribution to total emissions, degree of uncertainty, and influence on downstream outcomes. These included incoming butterfat content availability, milk component distribution, and product specifications. In future studies, we would require on-farm management information to test the impact of feed composition and manure management systems on the farm baseline and butterfat efficiences.

Butterfat content varies significantly across breeds and diets, prompting further scenario analysis (Figure 6). Observed inferences from the underlying data also guided variable selection. Variance and standard deviation analysis helped us distinguish between true variability in the system and data noise. We used these metrics to identify patterns in seasonal fluctuations (e.g., milk yield and butterfat content) and plant-level component distribution differences due to market conditions. These insights enhanced our confidence in interpreting the range of potential PCF outcomes under different assumptions.

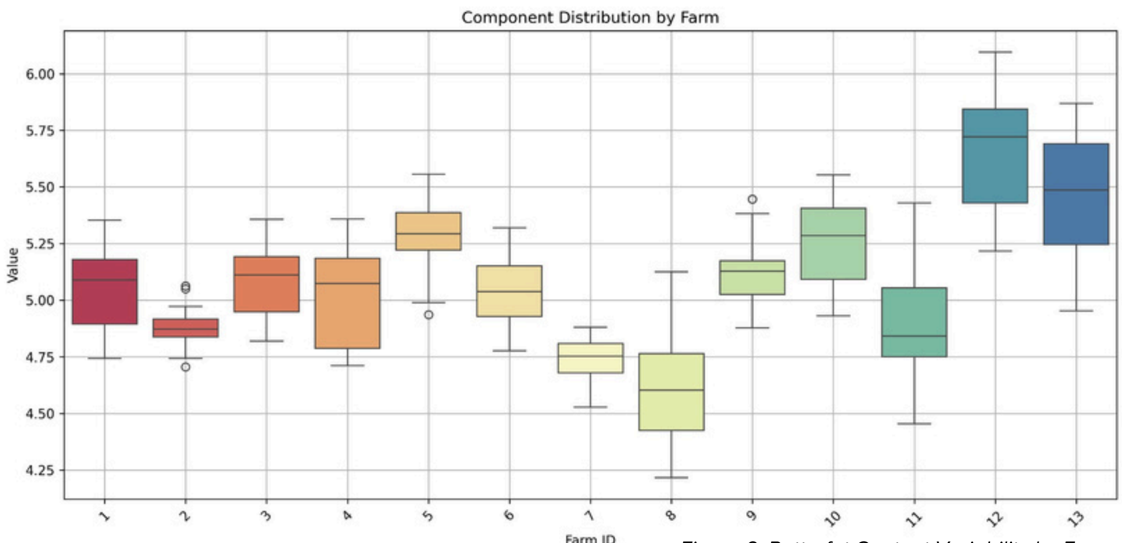


Figure 6: Butterfat Content Variability by Farm

Butterfat content plays a critical role in determining the carbon intensity of dairy products. Since the allocation of farm and transportation emissions are based on milk solids, fluctuations in butterfat and protein levels directly influence the product quantities and emission intensities. It is expected that products with lower fat content, such as lactose and protein isolates, inherit a greater share of emissions when butterfat increases, due to the greater availability of butterfat in raw milk and the amount of raw milk required to process end products. Exact product quantities were one of the challenges with the data collection and therefore limited the inferences that we can make about product quantity relationships.

Our analysis found a strong positive correlation between butterfat concentration and PCF of low-fat co-products. This relationship is illustrated through scatter plots showing the shift in PCF per kilogram of product as a function of milk component variability. Understanding these component-PCF interactions is critical for both accurate footprinting and informed decision-making on product design, labeling, and customer engagement.

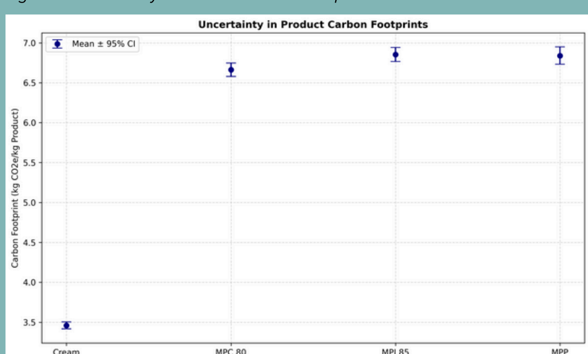
Uncertainty Assessment

We conducted Monte Carlo simulations to assess the uncertainty surrounding PCF estimates. These simulations incorporated probability distributions for key variables--including emission factors, allocation ratios, and milk composition--to generate a range of possible outcomes and identify confidence intervals around the reported PCFs. In all cases, 95% confidence intervals for PCF values fell within +/- 1% to 2% of the mean, depending on the product type and variability in its upstream emission drivers. Products with more variable or uncertain supply chains tend to have wider confidence intervals. We also ran predictive intervals to estimate the variability of individual data points given the incoming milk specifications.

- Cream shows the smallest percentage change in both lower and upper limits, indicating the least variability
- Protein concentrates exhibit moderate variability, which could be due to compounded variability in milk component distribution and processing energy intensity
- Permeate products display slightly higher variability, but the confidence intervals still fall within a relatively narrow range of about 2% in either direction

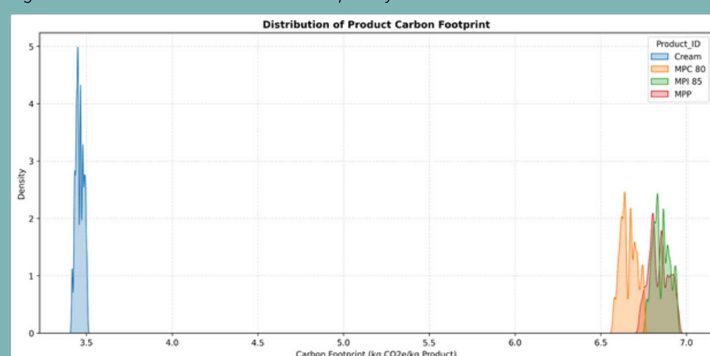
All data sources are within the same temporal and geographic ranges. The on-farm emission factors are sourced from FARM ES version 2, and future studies will analyze the sensitivity when adapting to version 3. The analysis is based on a 100% sampling rate across all farms in the raw milk input data. Following GHG Protocol Product Life Cycle Accounting and Reporting Standard data quality indicators (temporal, geographic, technological representativeness, as well as completeness and reliability of input data), strengthens the credibility of the outcomes.

Figure 7: Uncertainty in Product Carbon Footprints



Mean, Lower, and Upper Confidence Intervals that represent the 95% confidence level for each product.

Figure 8: Distribution of Product Carbon Footprint by Product



The distribution curve of carbon intensity values for each product represents a smoothed approximation of a histogram (raw frequency of data points).

The remaining sources of uncertainty include knowledge gaps such as the absence of site-specific enteric methane data, simplification of processing flows, and limited resolution on coproduct relationships–which all affect precision. However, by documenting these limitations and applying consistent methodological choices, the analysis supports credible and reproducible comparisons across products and scenarios. These steps ensure that the reported PCF values are accompanied by a transparent and defensible range, strengthening their utility for decision-making and comparison across different product mixes.

Discussion

Advantages, Challenges, and Opportunities

Clear economic boundaries, consistent allocation methodology, and continuous data quality improvements enable dairy processors, like Idaho Milk Products, to differentiate themselves to customers by increasing transparency and building trust with downstream buyers. As a result, customers are more likely to rely on cradle-to-gate emission factors derived from verified data, rather than the patchwork of estimation methods currently in use. On behalf of their supplying farms, IMP is capable of translating on-farm performance into product attributes, which positions the farms to capture carbon revenues within their value chains.

Developing the foundational emissions inventory highlights which aspects of the operation are difficult to measure at the activity level. However, this is largely a one-time effort, requiring updates only when material activities change. By investing in dynamic, operations-specific data management systems like BoundDairy, IMP is making a fundamental change to its accounting practices, unlocking carbon revenue for farmers through greater accuracy and allocation.

The long-term value of continuous product carbon footprinting lies in its ability to connect farm-level practices directly to end products, building confidence in the integrity of low-carbon product claims in the marketplace. This increased traceability allows for better accounting of carbon project impacts, facilitating collaborative investment in verified GHG reduction strategies and enabling transparent sustainability claims that hold up under scrutiny. Understanding the sensitivity and uncertainty of emissions outcomes further strengthens the strategic utility of PCFs for internal management, customer reporting, and carbon-related marketing.

Notably, PCFs can also support carbon-informed volume and pricing strategies. By assigning emissions to individual product groups and customer contracts, PCFs provide buyers with a clear view of the climate impact of their purchases–unlocking opportunities for price premiums, volume commitments, and other emissions-linked incentives. This helps processors like IMP translate emissions reductions into measurable market value.

In his role at Idaho Milk Products, Jeremy Pike can use BoundDairy's data infrastructure to provide real-time insights into supply specific emission profiles and present measurable results to link carbon performance to organizational decision-making.

Opportunity to Avoid Overallocation, Underallocation, and Double Counting

One notable feature of the BoundDairy approach to emissions accounting is that allocation of emissions to products is carried out by processors and then reported downstream. This contrasts with common practice today, where downstream food companies often estimate their upstream emissions, including product allocations. We believe that the system enabled by the BoundDairy approach is both more accurate and conducive to development of low-carbon dairy markets.

Today, downstream food companies have imperfect information about upstream operations and therefore must estimate the proportion of on-farm emissions that should be allocated to their dairy product purchases. While these methods are allowable under GHG Protocol frameworks, they introduce double counting, omission, and systemwide over- and under- allocation risks.

For example, one approach food companies use to estimate dairy ingredient emissions is through use of equivalence factors. This approach, however, relies on a variety of industry average assumptions about the fat, protein, and lactose contents of milk and the distribution of milk solids in a processing facility. Moreover, it does not account for potential differentials in fat, protein, and lactose production in farms with higher or lower emissions intensity. The result is a system where multiple food companies using equivalence factors may double count or omit emissions associated with their dairy products, leading to systemwide over- or under- allocation.

Equivalence factors approach to estimate dairy ingredient allocation

If a food company knows:

- 1 kg of butter typically requires ~20 L of raw milk
- The average emissions intensity of milk in a region is 1.2 kg CO2e / L FPCM
- Butter processing often uses nearly 100% of the fat content in a milk liter
- Fat is typically ~35% of milk solids content

Then the food company can estimate:

- Butter emissions are 8.4 kg CO2e / kg butter

*(20L milk * 1.2 kg CO2e / L FPCM * 35% of milk solids proportion)*

By contrast, in the BoundDairy system a processor has full visibility on the emissions factor of supplying farms as well as the milk quantity and quality from each farm. The processor also has detailed information about all of the product outputs coming from their facility. Therefore, the processor is able to do a more granular and accurate allocation, integrating milk solids and on-farm emissions intensity dynamics.

This key difference in allocation approaches is critical for the development of low carbon dairy markets. Similar to how the BoundDairy system enables processors to trace emissions associated with milk solids components and allocate them to end products, the BoundDairy system enables traceability of on-farm decarbonization projects and attribution of project claims to investing buyers. Notably, through these system-level allocation and attribution methods, processors can resolve double counting and free-riding concerns that are often challenges for decarbonization programs. Moreover, through system-level allocation methods, processors can create differentiated pricing for low-carbon products, setting up the foundation for premiums for low carbon production.

Benefits of Improved Accounting Practices

Streamlined Reporting
By leveraging existing aggregation points, such as raw milk intake and standardized production flows, IMP's dynamic PCF model focuses on meaningful, manageable data inputs. This strikes a balance of granular enough to reflect real change, but streamlined enough to avoid overburdening farms or operations.

Empowered Suppliers
While IMP has not yet implemented a reduction crediting system, the PCF model creates the foundation for doing so. By linking emissions outcomes to supplier-specific farm volumes and practices, it enables future attribution mechanisms, ensuring that verified GHG reductions can be credibly traced to participating farms.

Data Quality Evidence
The dynamic PCF model tracks emissions over time and links results to specific product types and volumes, enabling IMP to reflect seasonal changes in supply and customer-specific purchasing and market demand patterns. This adaptability is essential for modern GHG reduction strategies and accurate carbon claims.

Challenges
There are, of course, challenges with managing an emissions inventory for upstream activities, from data collection to quality of assumptions and uniqueness of business operations. The variability of reporting standards and customer requirements, such as CDP and SBTi, also may cause data management and reporting inefficiencies across value chain partners.

Lack of Farm Management Data
One of the most meaningful challenges is a lack of data inputs from the supplying farm leading to uncertainty in the baseline assumptions. Populating data gaps requires a hierarchical decision process that assumes the maximum carbon value (typically the national LCA factor). Cooperative or regional averages may be suitable, but it must be possible to exclude farm data that was used to calculate the averages to avoid double counting and incorrect baseline assumptions.

Frequent Raw Milk and Input Transfers Require Balancing
Similar to the on-farm boundary, a plant's economic boundary needs to account for incoming and outgoing ingredients. A cooperative may have surplus cream, as an intermediate product, going to an internal processing facility or being purchased by another company. A butterfat ingredient may be in high demand during certain seasons, necessitating supplementation with external cream inputs.

Cradle-to-farm and cradle-to-facility gate emissions associated with raw milk and inputs transferred to an internal plant or directly shipped to an external company are subdivided from the plant's emissions inventory. Incoming raw milk and other input transfers, however, are included in the plant's emissions inventory. Integrating purchase and sales orders into the carbon accounting methods ensures all emissions are correctly accounted, but it requires developing internal processes to enable collaboration between finance and sustainability teams.

Future Opportunities and Continuous Improvement Plans

Upcoming enhancements to BoundDairy's methodology include integrating GHG project data to integrate project-based and inventory accounting, establishing verification requirements, and developing the methodology to transfer emissions through the entire value chain from farm to retail.

Project-Inventory Integration

A key next step is enabling project allocations to product, which can then be allocated to customers based on investment activity. On-farm reductions can be linked to the farms that are supplying volumes to the facility where products are manufactured for customers. Variance in delivered volumes can be managed by connecting operations data with the accounting system, and contract agreements ensure investing parties receive their carbon attributes. The difference is that the BoundDairy Accounting system will improve the way emissions are reported to enable an auditable process.

Verification Standards

The market expectation is for verification to an auditable standard. With the ongoing uncertainty in the global carbon accounting space, BoundDairy Accounting will first develop a verifiable and transparent approach to ensure confidence in outcomes from the PCF methodology. The goal being that methodology and governance frameworks deployed within the accounting system can be the foundation for an improved verification system, with greater collaboration across the supply chain, and improved capacity for all cooperatives and processors.

Dairy Value Chain Emission Transfer Methodology

The Climate Source aims to develop the methodology and stakeholder buy-in for transferring product-level emissions data (including decarbonization project claims) through the value chain. In partnership with dairy companies and accounting experts, we plan to build a scalable, repeatable framework for accurate emissions accounting that supports investment in low-carbon ingredients.

Conclusion

Product-level Accounting Enables Credible Claims

BoundDairy Accounting supports the development of low-carbon dairy ingredients by building integrity in emissions data, strengthening allocation methodology and attribution mechanisms, and accelerating the path to market differentiation. By enhancing the International Dairy Federation's guidance to acheive full physical allocation of raw milk to finished dairy ingredients, this case study proves that the BoundDairy model and methodology significantly improves carbon accounting. Strict economic boundaries define the data requirements and product carbon footprint calculations based on the operational control of the cooperative and processor. And, the ability to integrate primary data sources with traceability from cradle-to-gate will satisfy customer demands for credible carbon reduction claims.

Economic boundaries, standardized data quality, physical allocation, and product attribution are cornerstones of carbon accounting frameworks. The BoundDairy Accounting approach operationalizes these requirements into a comprehensive system that is thus able to avoid the major risks of double counting, free ridership, and incorrect inventory reporting. With an understanding of dairy supply chain operational realities, The Climate Source goes beyond compliance and has established an accounting tool that aligns accounting requirements with the commercial value of low carbon dairy products.

For Idaho Milk Products, and its peers, this supplier-focused tool transforms a reporting challenge into a commercial advantage. BoundDairy's dynamic accounting system helps shift that focus back toward climate action, operational visibility, investment strategy, and product value. This physical traceability from cradle-to-gate also allows for proportional product matching, ensuring that investors in each milk component can optimize their dollars spent per ton of CO_2e reduced. This enables the valuation of stacked practices and blended emissions outcomes. With more data, cooperatives and processors will be better equipped to distinguish the effects of individual practices, understand trade-offs, and evaluate synergies, driving smarter investment and deeper impact.

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