MiLCA
Protocol for including Mitigation actions in Agricultural Lifecycle Assessment

Simmons, A.T[1]., Cowie, A.L.[2], Meyer, R.S.[3], Grant, T.[4], Macdonald, A. [3], Eady, S[4] Cheng, L. [5] and Eckard, R. [3]

[1] NSW Department of Primary Industries, Muldoon St, Taree NSW 2430 Australia

[2] NSW Department of Primary Industries, Trevenna Rd, Armidale NSW 2351 Australia

[3] The University of Melbourne, Royal Parade, Melbourne Victoria 3010 Australia

[4] Lifecycles, Smith Street, Collingwood VIC 3066, Australia

[5] The University of Melbourne, Dookie-Nalinga Road, Dookie College VIC 3647 Australia

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Contents

1 INTRODUCTION

Supply chains and consumers are demanding foods with lower **carbon footprint**s (CF), that remain safe to consume, in recognition of the need to address climate change. The dairy industry is responding to these demands by adopting technologies that reduce greenhouse gas (**GHG**) emissions from dairy production and it is expected that new technologies will continue to be developed. Confidence that **GHG emissions reduction**s are accurately quantified is required for CF claims associated with the implementation of a mitigation **technology** to be accepted by supply chains and consumers. This confidence can be provided by the global dairy industry adopting a consistent approach to objectively assess the robustness of mitigation technologies, and a **conservative** approach to estimating the **emissions reduction**s that occur. This protocol set outs criteria and approaches that, when applied to a **GHG** mitigation **technology**, will provide confidence to consumers and the supply chain that the claimed **GHG emissions reduction**s are robustly validated and their products are safe to consume.

The protocol provides guidance on determining whether a mitigation **technology** has adequate **evidence** to support its adoption by the dairy industry and the integration of the **GHG emissions reduction** associated with the implementation of the **technology** into a CF calculator. The **GHG emissions reduction**s can also be calculated manually if required. The approach to assessing the robustness of mitigation technologies and **conservative**ly estimating the **GHG emissions reduction** that can be claimed was developed to act as a foundation upon which a standardised approach to the provision of robust **GHG emissions reduction**s could be developed for all livestock sectors.

There are numerous initiatives developing guidance to ensure that quantification of **GHG emissions** and **emissions reduction**s in livestock sectors are robust. This protocol has been developed to integrate the concepts of **technology** efficacy with the quantification of an **emissions reduction** associated with the implementation of the **technology** and has drawn on the knowledge provided by members of other known initiatives to identify areas of complementarity. The protocol is a live document that will be updated as initiatives deliver results that are relevant to the objectives of the protocol and that, when integrated, improve the robustness of protocol outcomes.

This protocol is suitable to assess technologies as described in the definitions (section 3). It is not suitable to assess the **GHG emissions reduction**s associated with changes to dairy management practices that deliver **emissions reduction**s that are captured with existing **GHG emissions** calculations, such as through changes in herd productivity. The protocol does not include guidance on incorporating **carbon sequestration** in the CF of milk production; guidance for this is provided in the C seq guidelines (IDF, 2022a). Where a statistical regression approach (section 9.2.2) is used to calculate an **emissions reduction**, the protocol will require the calculation of a **prediction interval**. Determining the correct approach to generate a **prediction interval** may require the services of a statistician or biometrician.

The protocol consists of the main document and includes appendices with worked examples for two existing technologies as appendices and recommendations for future research that arose from the development of the protocol.

The following terminology is used throughout and is applicable to requirements with which protocol users need to comply:

- "shall" is used to indicate a requirement (mandatory).
- "should" is used to indicate a recommendation.
- "may" is used to indicate permission.
- "can" is used to indicate possibility.

2 PROTOCOL USE

The protocol provides guidance and requirements to quantify the **GHG emissions reduction** that can be claimed when a mitigation **technology** is implemented in a dairy system. It is applicable to mitigation technologies that can be implemented on dairy farms that target **GHG** sources such as **enteric methane**, on-farm fertiliser use and effluent management. The protocol is designed to be used in conjunction with the International Dairy Federation (IDF) CF guidance, "The IDF global **Carbon Footprint** standard for the dairy sector" (IDF, 2022b) and can also be applied to other methodologies and calculators. It provides guidance on the integration of the **emissions reduction** into a CF calculation. This is achieved by the calculation of the adjustment factor $GHG_{adj_{t(0.6)}}$ that is multiplied with the **GHG emissions** for a nominated source, as calculated by an existing CF methodology, to provide an adjusted estimate of **GHG emissions** for that source. This estimate can then then be integrated into a CF calculation.

The application of the protocol shall address five elements:

i. Description of the **technology** and implementation **context** (section 5) including the type, name and use of the **technology**.
ii. Demonstration of product safety (section 6) including regulatory approvals and consideration of the potential for any adverse environmental, animal

welfare, dairy **product quality** or human health consequences from the production or use of the **technology**.

iii. Collation of multiple pieces of **evidence** that supports the **technology** as an **emissions reduction** strategy (section 7)

iv. Assessment of quality of data used to estimate emissions (section 8)

v. Selection of **evidence** that is relevant to the system(s) being assessed as a basis for the calculation of an adjustment factor and the use of the **evidence** to calculate the adjustment factor (section 9).

A flow chart of the process is provided in APPENDIX A.

The protocol was written in the **context** of assessing **emissions reduction**s retrospectively however it can be applied prospectively evaluate a **technology** prior to adoption or project the **GHG emissions reduction** that may result from implementation.

3 TERMS, DEFINITIONS AND ABBREVIATED TERMS

Terms in the glossary are bolded throughout the document for reference.

Abatement

GHG removals by sinks and/or reduction in **GHG emissions** by sources

Baseline (Reference case)

A reference that provides the basis for comparison. In this document it refers to the system without use of the mitigation **technology**.

Biomass

Organic material excluding material that is fossilised or embedded in geological formations, including living and dead organic matter (trees, crops, grasses, plant litter, algae, animals, manure, and waste of biological origin).

Carbon

The chemical element with the symbol C.

Carbon credit

Tradeable certificate representing one tonne of carbon dioxide equivalents (CO2e) in **GHG** emission reductions, or **GHG removals**. **Carbon credit**s are generated by **GHG abatement** projects and quantified relative to a **baseline**. **Carbon credits** are commonly purchased to offset **GHG** emission of the purchasing entity.

Carbon crediting scheme

Buying and selling **carbon credits** generated by activities that reduce **GHG emissions** or achieve **GHG removals**. Emissions trading can occur in government markets (state, regional or national) and on the voluntary market. **Carbon credit** schemes commonly apply integrity criteria to ensure that the credits represent the stated **GHG abatement**. Integrity criteria commonly include, but are not limited to, the avoidance of double counting and **leakage**, use of appropriate baselines, additionality, and permanence or measures to address impermanence.

Carbon dioxide (CO_2)

A naturally occurring greenhouse gas, that is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning **biomass**, of land use changes and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other **GHG**s are measured and therefore has a Global Warming Potential (**GWP**) of 1. (Cowie et al., 2023)

Carbon dioxide equivalent (CO_2-e)

Unit for comparing the radiative forcing of a **GHG** to that of carbon dioxide. The carbon dioxide equivalent is calculated as the mass of a given **GHG** multiplied by its global warming potential.(Cowie et al., 2023)

Carbon footprint

Sum of **GHG emissions** minus **GHG removals** of the subject expressed as carbon dioxide equivalents (CO2-e). The subject could be a product or an organisation. Where the subject is an organisation, such as a company, the CF often includes **Indirect emissions** also known as **scope 2** and **scope 3** emissions. Where the subject is a product, the CF includes the emissions and removals across the product life cycle. (Cowie et al., 2023) For farm products, a partial CF is often calculated, covering the life cycle stages up to the farm gate, or factory gate in the case of dairy products.

Carbon neutrality

Condition in which anthropogenic **GHG emissions** associated with a subject are balanced by anthropogenic **GHG removals**. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service or an event.

Carbon sequestration

The process of removing carbon dioxide from the atmosphere and transferring it to a carbon pool such as vegetation, soil, ocean or geological formation. (Cowie et al., 2023)

Claimable emissions reduction

Reduction in **GHG emissions** that can be claimed due to implementation of a **technology** as calculated by subtracting the adjusted **GHG emissions** calculated by this protocol from the estimated **GHG emissions** without the implementation of the **technology**.

Conservative (in this protocol)

Claimable **GHG emissions** reduction that is less than the mean **GHG emissions** reduction from experimental results.

Context (in this protocol)

The system in which the **technology** is intended to be applied. Includes the geography and feeding pattern (*i.e.* total mixed ration or pasture-based).

Data quality

Relevance of the data used in emissions reductions calculations to the system being assessed. Includes the source of the data, system representativeness, temporal suitability, and geographical suitability.

Emissions

See **Greenhouse Gas Emissions**

Emissions reduction

A decrease in **GHG emissions** when compared to business-as-usual

Enteric methane

Methane formed during the digestion process of ruminant animal species such as cattle, sheep, goats, etc. Microorganisms (bacteria, archaea, fungi, protozoa and viruses) present in the fore-stomach (reticulorumen or rumen) breakdown plant Biomass to produce substrates that can be used by the animal for energy and growth with **enteric methane** produced as a by-product. Fermentation end-products such as hydrogen, carbon dioxide, formate and methyl-containing compounds are important substrates for the production of **methane** by the rumen's **methane**-forming archaea (known as methanogens).

Estimation

A value that has been obtained without measurement. A qualified **estimation** is one that has been made by a person with relevant expertise in the form of formal qualifications and experience. An unqualified **estimation** is one that has been made by a person without the relevant expertise in the form of formal qualifications and experience.

Evidence

See **Piece of evidence**

Experiment (in this protocol)

A scientific procedure undertaken to compare the impacts of a **technology** (in this protocol) on the **GHG emissions** from a **farming system**(in this protocol). A treatment group compared to a control group constitutes 1 **experiment**; more than one **experiment** can be included in a single publication.

Farming system(in this protocol, also ‘system’)

The set of components and management that produces dairy products, including, the facilities, animals, and feed base, as listed in Section 5.1.3.

Global warming potential (GWP)

An index measuring the radiative forcing following an emission of a unit mass of a **GHG**, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO2). The **GWP** represents the combined effect of the differing times that **GHG**s remain in the atmosphere and their different effectiveness in causing radiative forcing, that is, in heating the Earth’s atmosphere. **GWP** is measured in units of carbon dioxide equivalents (CO2e). The most common time horizon is 100 years (**GWP**100).

Parties to the **UNFCCC** have agreed to use **GWP**100 values from the **IPCC**’s Fifth Assessment Report (AR5) or **GWP**100 values from a subsequent **IPCC** Assessment Report to report aggregate emissions and removals of **GHG**s under the Paris Agreement.

$\boldsymbol{GHG_{adj_{t(0.6)}}}$

A decimal number between 0 – 1. It is a factor calculated by the use of the protocol and is multiplied by the baseline **GHG emissions** for the relevant source as calculated using a relevant existing **GHG accounting** framework. This provides an estimate of the **GHG emissions** for that source when the **technology** is implemented in a dairy system.

Greenhouse gas (GHG)

Gaseous constituent of the atmosphere, either natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), **methane** (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth’s atmosphere. Human-made **GHG**s include sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs).

Greenhouse gas accounting (GHG accounting)

The process of compiling a chart of accounts that reports the inventory of **GHG** emissions, detailing the emissions and removals of each **GHG**, from each source and **sink** process, over a specified period, typically one year. For agricultural systems, that are often subject to wide annual variation, the data are often derived by averaging over a period of five or ten years.

Greenhouse gas emissions (GHG emissions or emissions)

Release of a **GHG** into the atmosphere; **GHG emissions** result from a **GHG** source

Greenhouse gas removals (GHG removals)

Anthropogenic activities that remove carbon dioxide from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products. Carbon dioxide removal methods include afforestation, reforestation, biochar, bioenergy with carbon dioxide capture and storage (BECCS), soil **carbon sequestration**, enhanced weathering, direct air carbon capture and storage (DACCS), ocean alkalinisation and ocean fertilisation. A carbon dioxide removal activity initiates a **sink** process that leads to **GHG removals**.

Indirect emissions

GHG emissions that are a consequence of the organisation's activities, but that arise from **GHG** sources that are not owned or controlled by the organisation. **Indirect emissions** occur upstream and/or downstream of the farm, across the value chain, and include emissions from manufacture of inputs such as fertiliser, and from processing of products, such as abattoir operations or milling. **Indirect emissions** also include emissions outside the value chain that are induced by change in demand for (or supply of) products produced or sourced by the organisation.

International Panel on Climate Change (IPCC)

An intergovernmental body of the United Nations established in 1988 to provide scientific information on anthropogenic climate change, including the impacts and risks, and response options. The **IPCC** does not conduct original research but rather undertakes periodic, systematic reviews of published literature. **IPCC** reports are prepared by thousands of scientists and other experts who volunteer to assess the science related to climate change. The **IPCC** is governed by its member states through an elected bureau of scientists, who select the authors for each report from nominations received from governments and observer organisations.

Leakage

An increase in emissions that results indirectly from mitigation actions. **Leakage** can include increased **GHG emissions** upstream or downstream in the value chain (such as increased emissions associated with the implementation of a **technology**), or through market-mediated effects (such as indirect land use change to produce a commodity elsewhere, in response to a decline in production in the system being assessed).

Life cycle assessment (LCA)

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle refers to "cradle-to-grave": the consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal or recycling. In **LCA** of farm products, partial **LCA** is common, often covering cradle to farm gate.

Meta-analysis

A statistical analysis of the results of several experiments (in this protocol)

Methane

A potent greenhouse gas with short atmospheric lifetime. **Methane** is the major constituent of natural gas. Livestock production and paddy rice are significant **methane** sources. **Methane** is produced naturally when organic matter decays under anaerobic conditions, such as in wetlands.

Mode of action (in this protocol)

The physical, biological and/or chemical process that result/s in a reduction in **GHG** emissions

Piece of evidence

Can refer to either a set of experimental results, with multiple pieces of evidence able to be presented in one publication, a **meta-analysis** of a **technology**, or an existing methodology from an ICROA-accredited **carbon crediting scheme**.

Prediction interval

An estimate of an interval (*i.e.* upper and lower values) in which a prediction for a variable generated by populating an equation will fall, for a given probability.

Primary data

Quantitative measurement of activity from a product life cycle that is required to calculate **GHG emissions** or the reduction in emissions associated with a **technology**. For example, amount of chemical added to effluent or diet quality factors that can influence efficacy of feed additives.

Product quality

The quality of milk that is produced in a dairy in which a **technology** has been implemented. Refers to debris and sediment, flavour, colour and odour, bacterial count, existence of introduced chemicals, and composition and acidity.

Reporting period (in this protocol)

The period for which the **carbon footprint** of the **farming system**is being calculated.

Scope 1, 2, 3 emissions

Terminology developed by the Greenhouse Gas Protocol and now adopted broadly

Scope 1 emissions: direct emissions arising from sources within the control of the reporting organisation.

Scope 2 emissions: **Indirect emissions** from the generation of purchased or acquired electricity, steam, heating or cooling consumed by the reporting organisation.

For farms, this is predominantly electricity use.

Scope 3 emissions: **Indirect emissions** other than scope 2 emissions that occur within the value chain as a consequence of the organisation's activities. For farms, scope 3 emissions are the pre-farm and post-farm emissions, such as from manufacture of urea and herbicides, processing in abattoirs, and refrigerated transport of produce.

Secondary data

Data obtained from sources other than direct measurement of the **farming system.** Note that **secondary data** were used when **primary data** were not available or it is impractical to obtain **primary data**. **Secondary data** *should* also be based on peer-reviewed scientific literature, government statistics, or reports published by international institutions confirming the estimated value and associated uncertainty over multiple studies.

Sink

A process, activity or mechanism that removes a **GHG**, an aerosol or a precursor to a **GHG** from the atmosphere. A pool (reservoir) is a **sink** for atmospheric carbon if, during a given period, more carbon is moving into it than is flowing out.

Source

A process, activity or mechanism that releases a **GHG**, an aerosol or a precursor to a **GHG** into the atmosphere. Forests and agricultural lands are reservoirs: they can be either a **GHG source** or a **sink**.

Technology (in this protocol, also referred to as mitigation **technology**)

A product that reduces **GHG emissions** from a dairy farming system. The product can reduce **GHG emissions** via biological or chemical processes or can be a device. Examples of technologies include, but are not limited to, supplements to reduce **enteric methane** production, additives to reduce **GHG emissions** from effluent systems and coatings to reduce on-farm emissions associated with N fertiliser use. It specifically excludes products designed to sequester atmospheric C and the introgression of low-**methane** genetics into dairy herds.

United Nations Framework Convention on Climate Change (UNFCCC)

International treaty that aims to achieve the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system.

Use (in this protocol)

The process that is used to implement the **technology**, such as the rate and the frequency with which the **technology** is implemented and/or the period of time during the year that the **technology** is implemented.

4 ALIGNMENT WITH EXISTING STANDARDS

This protocol uses terminology and concepts that are consistent with **GHG** reporting and accounting at the corporate level, including for mandatory reporting, voluntary target-setting, environmental claims and the voluntary carbon market.

The protocol is designed to generate values that can be used in conjunction with CF calculators to enable the calculation of a reduced CF for products from dairies that have implemented a mitigation **technology**. Though it is designed to be integrated into CF calculations under the IDF **carbon footprint** standard (IDF, 2022b) it can also be applied in other CF or **LCA** tools. For example, it could be used in product level **carbon footprint**ing using:

- Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard
- ISO 14067 **Carbon footprint** of products
- ISO 14068 **Carbon neutrality** (applied to a product).

The IDF standard provides comprehensive guidance on quantifying the **carbon footprint** of dairy products in accordance with the ISO **LCA** standards 14040 and 14044. Topics covered include setting the system boundary, choosing the functional unit, handling co-products (allocation), data collection, and land use change, all of which are complex in the dairy sector, requiring tailored guidance. The IDF standard makes provision for the inclusion of mitigation technologies in CF calculations, recognising the need for **evidence** of efficacy, and specific guidance on quantification. This protocol is designed to address that need.

The protocol outputs could also be used by companies in preparing **GHG** inventories such as for voluntary claims related to **carbon neutrality**, **carbon footprint** reduction and net zero **GHG** targets, or for climate-related financial disclosure under the International Sustainability Standards Board (ISSB) standards and national equivalents, where consistent with the methodologies specified by these programs. The protocol could be used in conjunction with the following standards for corporate **GHG** reporting:

- Greenhouse Gas Protocol Corporate Standard
- Greenhouse Gas Protocol **Scope 3** Standard
- Greenhouse Gas Protocol Agricultural Guidance
- Greenhouse Gas Protocol Land Sector and Removals Guidance (to be released in Q3 or Q4, 2024)
- Science-based targets initiative (SBTi)
- ISSB IFRS S2 Climate-related disclosures

- ISO 14064-1 Organization level quantification and reporting of **GHG emissions** and removals
- ISO 14064-2 Project level quantification, monitoring and reporting of **GHG** emission reductions or removal enhancements
- ISO 14068 **Carbon neutrality** (applied to an organisation).

The protocol generates qualitative information and data that could be used to support a product-based environmental claim such as under the ISO 14021, Environmental labels and declarations for self-declared claims, or ISO 14025 Environmental labels and declarations Type III environmental declarations, for environmental product declarations (EPD).

The protocol requires information from a full life cycle assessment (**LCA**) that has been conducted in accordance with ISO 14040 and ISO 14044.

The IDF **carbon footprint** standard provides an overview of many of the standards and guidelines listed above, including their application to quantifying the **carbon footprint** of dairy products.

5 TECHNOLOGY AND IMPLEMENTATION CONTEXT

*How and where the **technology** will be implemented needs to be clearly stated to ensure information provided in the latter sections of the protocol is relevant to the **technology** and the specific implementation of the **technology** being assessed by the protocol.*

5.1 SCOPE

The scope of the **emissions reduction** assessment shall be defined by unambiguously describing the following:

i. The **technology** (see **Error! Reference source not found.**)
ii. The intended **use** of the **technology** (see 5.1.2)
iii. The system(s) in which the **technology** will be implemented (see 5.1.3)
iv. The period over which the **technology** will be implemented (see 5.1.4)

5.1.1 TECHNOLOGY

A report prepared in accordance with this protocol shall unambiguously identify the **technology**. The identification of the **technology** shall include, where applicable, the product name, trade name, manufacturer and/or active ingredient/s and/or the **mode of action**.

5.1.2 USE

The **use** of the **technology** shall be described. This description shall contain the following information, where applicable: targeted **GHG** source, concentration or dosage, method of **use**, frequency of **use** and proportion of the **reporting period**, during which the **technology** will be used section 5.1.4. Where applicable, any requirements set out by the manufacturer with regards to the **use** of the **technology** (section **Error! Reference source not found.**) to achieve **emissions reduction**s shall be attached to the report and shall be included in the description of **use**.

5.1.3 SYSTEM

The system in which the **technology** was implemented shall be described. This description shall contain, where applicable, the following information:

i. Location, including climate and soil type
ii. Breed, including weight
iii. Whether the herd is self-replacing
iv. Productivity (e.g. fat and protein corrected milk production)
v. The proportion of the year the animals are housed
vi. The type of manure management system (required for manure management technologies only)
vii. The composition of the diet by season or month (*i.e.* the proportion of the dry matter intake that is pasture, grain, silage and/or supplements)
viii. The quality of the diet

Where any information changes during the year due to seasonal conditions or the availability of inputs (*e.g.* a change in the quality of supplied feed), points (i) through (viii) shall be documented on a seasonal basis and/or for each change.

5.1.4 IMPLEMENTATION PERIOD

The proportion of the **reporting period** (*i.e.* period for which the CF is being calculated) during which the **technology** was implemented and for which a **GHG emissions reduction** is being estimated shall be documented.

6 SAFETY

*The acceptance of mitigation technologies by policy makers, industry and consumers requires demonstrating that the **technology** is safe to use, with respect to impacts on human health, animal health and the environment. This section provides minimum criteria that must be met by technologies to provide confidence that the implementation of the **technology** will have minimal adverse impacts. The assessment of environmental impacts under section 6.2 has been adapted from global frameworks on life cycle assessment including ISO-14044.*

6.1 REGULATORY APPROVALS

Written **evidence** of regulatory approval for the **technology** (**Error! Reference source not found.**) used as described (5.1.2) in the system (5.1.3) shall be attached to the report. This includes approvals by the appropriate organisations for commercial use of the **technology** as well as occupational health and safety regulations for the **technology**.

6.2 ENVIRONMENTAL IMPACTS

Results from a **LCA** of the manufacture and **use** of the **technology** as described (5.1.2) in a system that shares the characteristics documented in (5.1.3) shall be presented. The **LCA** shall be compliant with ISO 14044 (International Organization for Standardization, 2019) including an independent review. The **LCA** shall provide the impacts as absolute values (characterisation) and relative to the current production system without the proposed **technology**.

The **LCA** shall include a comprehensive set of environmental indicators including but not limited to **GHG** emissions. Indicator selection shall be relevant to the product system. For example, if the **technology** affects productivity, then water scarcity (Boulay et al., 2018) and land use impacts on soil quality (Bos et al., 2020; Brandão et al., 2011) would be necessary. If the **technology** emits ozone depleting substances, then ozone depletion (World Meteorological Organization (WMO), 2014) would be required. Any **technology** based on a chemical additive should include human toxicity (cancer and non-cancer) (Fantke et al., 2021). Recommended indicators lists for different technologies is included in APPENDIX E.

As different indicators are not of equal importance it not practical to set thresholds of impact increase in non-greenhouse gas indicators which can be tolerated in a **GHG abatement technology**. What **LCA** can provide is transparent information on relative impact increases or decreases to ensure unintended impacts can be assessed by users of that **technology**. As such the risk of adverse environmental consequences shall be discussed as part of the protocol.

6.3 IMPACTS TO THE FARMING SYSTEM

Given that minimum standards of health and safety for both animals and humans have been addressed in Section 6.1 and the decisions regarding appropriate trade-offs vary on **context**, there is no threshold associated with farm impacts. What is required is a disclosure of the known information citing original peer-reviewed research and identification of knowledge gaps regarding impacts on production, **product quality**, and animal health and welfare. A list of all reviewed, original literature (i.e. not reviews) on these topics and the databases and search terms used to find these articles should be included.

This section shall review the consequences of using the **technology** on animal welfare and impact on product quality or production. If any of this information is not available, the information gap needs to be acknowledged. Where the implementation of a **technology** results in a decrease in production then the magnitude of the reduction shall be reported, due to the risk of **leakage** associated with a decrease. Changes in production also need to be captured in the CF calculation to reflect resulting changes in emissions per unit product.

7 DEMONSTRATING EFFICACY OF A TECHNOLOGY

*Confidence that the implementation of the **technology** will result in a consistent and reliable reduction in **GHG emissions** is important for the acceptance of claimed **GHG emissions reductions** associated with implementation of that **technology**. This is achieved by providing **evidence** either as results from multiple scientific experiments that have demonstrated effectiveness of the **technology** or as a methodology approved under an existing accredited **Carbon crediting scheme**. Both forms of **evidence** have minimum requirements that must be met to ensure that the **evidence** provided is robust, which are described in this section.*

*The more pieces of **evidence** available the greater the confidence in the assessment of a **technology** therefore, it is imperative that as many pieces of **evidence** as possible are provided to support assessment of the efficacy of the **technology**. However, the results of experiments are not always published or made available in the public domain. Therefore, the authors acknowledge that this protocol is limited by the* *reality that generally only experiments showing a statistically significant positive or adverse effect of a treatment are published in scientific journals, and some experimental results are confidential, held by commercial companies.*

7.1 DEMONSTRATED REPEATABLE REDUCTIONS

A consistent reduction in **GHG emissions** associated with the implementation of the **technology** shall be demonstrated using one of the following:

i. a **meta-analysis** demonstrating a statistically significant (P ≤ 0.05) **GHG emissions reduction** associated with the **use** of the **technology**, that meets the requirements for experimental settings and scientific publications specified in section 7.2. A copy of the publication shall be attached to the report if it is not open-access, and if it is open access, the digital object identifier (DOI) shall be provided.

ii. a minimum of three (3) experiments that:

   a. demonstrate a statistically significant (P ≤ 0.05) reduction in **GHG** emissions, and

   b. that meet the requirements for experimental settings and scientific publications specified in section 7.2

   Copies of the scientific publication(s) containing results of these experiments shall be attached to the report if they are not open access and if they are open access, the DOI shall be provided.

iii. An existing methodology from a **Carbon crediting scheme** that meets the minimum requirements set out in section 7.2.2.

A statement shall be made for each **piece of evidence** outlining how the requirements in section 8.2 are met.

7.2 REQUIREMENTS FOR PIECES OF EVIDENCE

7.2.1 EXPERIMENTAL SETTINGS AND SCIENTIFIC PUBLICATIONS

Where a **meta-analysis** (8.1 option (i)) or set of experimental results (8.1 option (ii)) are used as **evidence**, the protocol user shall justify that the experimental results are applicable to a commercial dairy situation.

Experimental results that have been published in a journal that was classified as a level 1 or 2 journal on the Norwegian Register For Scientific Journals, Series and Publishers at the time of publication shall be used as **evidence**. Documentation showing that the journal was a level 1 or 2 journal at the time of publication shall be attached to the report.

Experimental results from experiments that do not include a control shall not be used.

7.2.2 EXISTING METHODOLOGIES

Calculations from an approved **Carbon crediting scheme** methodology may be used to calculate the **claimable emissions reduction** (see 7.2.2). if

i. that methodology is from a standard endorsed by the International Carbon Reduction and Offsetting Accreditation (ICROA) program and
ii. it provides a **conservative** estimate of **GHG emissions reduction** by using statistical uncertainty to adjust the **GHG emissions reduction**, and the estimate calculated using the methodology is as **conservative** as that calculated using this protocol, or data are provided that allow adjustment such that the estimate of **emissions reduction** can be adjusted to be as **conservative** as that calculated using this protocol.

8 DATA QUALITY

The calculation of a claimable ***GHG emissions reduction*** *requires data for a dairy production system. Data can be* ***primary data*** *(i.e. data that are specific to the system being assessed) or* ***secondary data*** *(i.e. data obtained from another system and applied to the system being assessed).* ***Secondary data*** *are lower quality data however in some instances* ***secondary data*** *may be the only data available to calculate the claimable* ***GHG emissions reduction****. Using lower quality data to calculate a* ***GHG emissions reduction*** *reduces the accuracy of the calculation and has the potential to reduce the acceptance by the target audience of* ***GHG emissions reduction*** *claims by the dairy sector. Adjusting the* ***claimable emissions reduction*** *for the quality of data used demonstrates to the target audience that the dairy sector acknowledges that using lower quality data impacts the confidence in the efficacy of* *a* ***technology****. A* ***data quality*** *adjustment has a number of other benefits including incentivising the use of high-quality data to maximise the* ***claimable emissions reduction*** *and ensuring the protocol is flexible enough to be applied to yet-to-be-developed technologies that may require data that is inherently difficult to obtain and will therefore by necessity be low-quality.*

The approach to ***data quality*** *used in the protocol is adapted from the data pedigree matrix approach used by the global life cycle assessment community (Ciroth et al., 2016). A factor with which to adjust a* ***claimable emissions reduction*** *is calculated based on the quality of data used to calculate the* ***claimable emissions reduction****. The integration of this factor adds statistical uncertainty to the equations used to calculate the* ***claimable emissions reduction*** *when data used is not of the highest possible quality. This increase in statistical uncertainty increases the* ***prediction interval*** *resulting in a greater adjustment of the estimated* ***emissions reduction****.*

The quality of the data used to calculate an **emissions reduction** is determined by four categories as described below. The levels for each category are presented in APPENDIX and the **data quality** adjustment is described in sections 9.2.1 and 9.2.2.

i. DATA SOURCE

This criterion evaluates the quality of the data based on the method of obtaining the data. It assesses whether the data are obtained via direct measurements, a calculation or a qualified estimate.

ii. SYSTEM REPRESENTATIVENESS

This criterion assesses the extent to which the on-farm data used to estimate the **emissions reduction** represent the system being assessed. Data that are obtained from the system being assessed are considered higher quality than data that are obtained from other system or regional averages. Milk output per cow is used to determine representativeness because it reflects the system with respect to feedbase and livestock movement (*i.e.* barn systems with high quality feed and limited movement are likely to have higher productivity than a pasture-based system with lower quality feed where cows walk further, so use more energy).

iii. TEMPORAL SUITABILITY

This criterion evaluates the extent to which data are up-to-date and applicable and, therefore, relevant to the **reporting period** covering relevant events and trends.

iv. GEOGRAPHICAL SUITABILITY

Geographical suitability examines whether the data's geographic scope match the area of interest for the system being assessed. This ensures that the data are applicable to the specific location or region of concern.

8.1 DATA QUALITY ASSESSMENT

The data source and relevant **data quality** adjustment factor for each of the variables used to calculate **emissions reduction**s shall be documented in a table. **Data quality** adjustment factors for each **data quality** category are given in APPENDIX B.

9 CALCULATION OF CLAIMABLE EMISSIONS REDUCTION

*Providing confidence that the **claimable emissions reduction** associated with the implementation of a **technology** is robustly validated is achieved using the following four strategies:*

1. *The use of robust scientific results from the **evidence** that is most relevant to the system under study as the basis for **GHG emissions reduction** calculations. The scientific **evidence** must meet requirements (7.2) and be relevant to the **technology** and **context** as described in section 5.*

2. *The calculation of a **conservative** estimate of the **GHG emissions reduction**, where the magnitude of the **emissions reduction** is adjusted according to the uncertainty of the experimental results to determine the **claimable emissions reduction**. such that the emission reduction is reduced in proportion to uncertainty. This provides an incentive to **technology** developers and researchers to generate and publish high quality experimental results. Adjusting **GHG emissions reduction**s based on statistical uncertainty is a relatively common approach to ensure the integrity of **GHG emissions** reduction claims and is a basic principle of the Verra Carbon Standard (Standard, 2022) and is also included in government **carbon credit** methodologies (Australian Government, 2021). In this protocol, the **claimable emissions reduction** is the value for which there is 60% chance of exceedance.*

3. *The adjustment of the calculated **GHG emissions reduction** for the quality of data that is used to calculate the **emissions reduction**. Adjusting the calculated **GHG emissions reduction** for **data quality** incentivises the collection and use of the highest possible quality data from the system being assessed and provides flexibility in the data that can be used.*

4. *The estimated **GHG emissions reduction** is re-calculated on an annual basis or whenever new information that improves an estimate of **GHG emissions reduction** becomes available.*

9.1 EVIDENCE USED FOR CALCULATIONS

The **evidence** used for calculations shall be one of either:

i. A **meta-analysis** that meets requirements set out in section 7.1.i.

ii. The provision of experimental results that demonstrate a significantly significant ($P \leq 0.05$) reduction in **GHG emissions** when compared to a control for the **technology** (**Error! Reference source not found.**) when used (5.1.2) in a system as described (5.1.3). These experiments must meet the requirements as set out in section 7.1.ii.

iii. Where more than one set of experimental results have equal relevance to the system being assessed, as described above in 9.1.ii, and it is statistically appropriate to average the experimental results as determined by a qualified statistician, then the results shall be averaged and the average used to calculate an **emissions reduction**.

iv. An existing methodology from a **GHG abatement** scheme that meets the minimum requirements set out in section 7.2.2.

Where multiple pieces of **evidence** are available, the **evidence** that is the most relevant to the system being assessed shall be used.

If unrestricted online access is available, the DOI or other permanent digital identifier for the relevant document shall be provided. Otherwise, a copy of the relevant document shall be provided. Where multiple sets of experimental results are averaged, a report from a statistician detailing the method used to derive the average shall be provided.

Evidence shall only be used in calculations of **claimable emissions reduction** where these criteria are met:

i. The implementation of the **technology** in the **evidence** used to calculate **claimable emissions reduction** shall be consistent with the implementation **context** described in section 5.1.2. The protocol shall not be used to assess the implementation of a **technology** where these uses are inconsistent. This includes, where relevant, the concentration declared under section 5.1.2.

ii. Where the **evidence** used to calculate an **emissions reduction** is a regression equation, the values of data used to populate the equation to estimate the **emissions reduction** shall not exceed the range of values for the relevant variable used to develop the equation.

iii. Where the **GHG emissions reduction** is dependent on the environmental conditions that change over time (*e.g.* on a seasonal basis), then a **GHG emissions reduction** shall only be calculated where the environmental conditions declared in section 5.1.2 are the same as those under which the **evidence** used to support calculation under section 9.1 were obtained.

iv. Claims for a **GHG emissions reduction** should not exceed the maximum duration of the **experiment** in the **evidence** used as a basis for **GHG emissions reduction**s calculations. It is common for biological systems and processes (*e.g.* using a chemical to change the activity of one group of microbes in an environment with a diversity of microbe groups) to adapt to changes. It is also likely that indications of adaptation will be observable over a period of months, as opposed to years. If the period of claim exceeds the maximum duration then the longer period of claim shall be justified. Justifying a longer period shall rely on published scientific literature and consider the **mode of action** for the **technology**, the vulnerability of the **technology** to adaptation and the absence of adaptation in **experiments** of a duration in which adaptation could be expected to occur.

v. If the **evidence** comes from experiments conducted in a different system, or in the same system under different diet compositions (5.1.3), the user shall justify that the **evidence** used in calculation of **claimable emissions reduction** is applicable to the system under study. Justification is qualitative and shall address the following components (where relevant to the declared **technology**); animal mass, milk production, diet type, diet quality, climate, soil type (as described using the surface soil texture) and describe the proportion of year that that changes in any of these components occurs.

If used as **evidence**, an external **GHG abatement** scheme methodology shall be strictly limited to the **use**/system defined within the methodology.

A statement outlining how these criteria are met shall be provided.

9.1.1 UNCERTAINTY ADJUSTMENT

Where a methodology from an existing **Carbon crediting scheme** is used, and the **emissions reduction** calculated by the methodology is less **conservative**, the calculations contained in the methodology shall be adjusted so the calculated **emissions reduction** is as **conservative** as that calculated using this protocol.

9.2 EQUATIONS

*Statistical knowledge and/or an understanding of **prediction intervals** may be needed to undertake the calculations specified in this protocol, so the input of a statistician may be necessary to implement the protocol. The equations used to calculate the factor required to calculate the **claimable emissions reduction** are dependent on the statistical analysis used in the **evidence** (section 9.1). Where the calculation of **GHG emissions reduction** uses the difference in absolute emissions between a control and treatment assessed by a parametric statistical method, a factor with which to calculate a **claimable emissions reduction** shall be calculated using equations in section 9.2.1. Where the **GHG emissions reduction** is calculated using an equation developed using a parametric statistical method, a factor with which to calculate a **claimable emissions reduction** shall be calculated using equations in section 9.2.2. Guidance when a non-parametric statistical method has been used is provided in 9.2.3. It is difficult to provide specific equations for calculating the **claimable emissions reduction** when an equation is used due to the different statistical analyses that can be used to generate an equation for calculating **emissions reductions**. As such, the equations presented here are high level and the application of the equations will likely require the input of a statistician or biometrician. Experimental data analysed using non-parametric analysis methods can also be used and requires a statistician to ensure the calculations used are appropriate.*

The protocol generates $GHG_{adj_{t(0.6)}}$, an adjustment factor expressed as a decimal that is used to adjust an estimate of **GHG emissions** from the relevant **GHG** source without the **technology** implemented as calculated by an existing CF methodology.

For all equations presented in this sub-section:

- Where a mixed model approach was used for statistical analysis in the **evidence** and random effects in the model were statistically significant then the predicted values shall be used.
- Where a co-variate was included in the statistical analysis in the **evidence** and found to be significant then values adjusted for co-variance shall be used.

9.2.1 DIFFERENCE BETWEEN THE MEANS OF A CONTROL AND A TREATMENT

Where a statistically significant **GHG emissions reduction** is demonstrated between the control and a treatment, the factor, $GHG_{adj_{t(0.6)}}$, that is used to adjust the **GHG emissions** using a CF method may be calculated using Equation 1. $GHG_{adj_{t(0.6)}}$ may alternatively be calculated via another method (*e.g.* Fieller's theorem) when the calculations are done by a qualified statistician. Those calculations shall include an adjustment for the specified probability of exceedance and be appropriately adjusted for DQ , and be attached in a report provided by the statistician.

Equation 1

$$GHG_{adj_{t(0.6)}} = \frac{\bar{x}_c - x_a}{\bar{x}_c}$$

where $GHG_{adj_{t(0.6)}}$ is the value used to adjust the emissions as calculated without the **technology**, $\bar{x}_c$ is the sample mean of the control from the **experiment** and x_a is the difference between the control and treatment groups adjusted for statistical uncertainty and **data quality** using Equation 2.

Equation 2

$$x_a = \bar{x}_d + t_{(0.6,df)} \cdot \Delta_{diff}$$

where $\bar{x}_d$ is the difference between the estimated means of the control and treatment groups as calculated using Equation 3, $t_{(0.6)}$ is the critical lower one-tail value from the t-distribution for the relevant df, as calculated by Equation 4, based on a 60% confidence level and Δ_{diff} is the adjusted uncertainty associated with the measurement of the control and treatment samples or populations as calculated using Equation 4.

Equation 3

$$\bar{x}_d = \bar{x}_c - \bar{x}_t$$

where $\bar{x}$ and $\bar{x}_t$ are the means of the control and treatment groups, respectively, as taken from the **evidence** declared in section 9.1.

Equation 4

$$df = \frac{(SE_{\bar{x}_c}{}^2 + SE_{\bar{x}_t}{}^2)^2}{\left(\frac{SE_{\bar{x}_c}{}^4}{df_{\bar{x}_c}} + \frac{SE_{\bar{x}_t}{}^4}{df_{\bar{x}_t}}\right)}$$

where $SE_{\bar{x}_c}$ and $SE_{\bar{x}_t}$ are the standard errors of $\bar{x}_c$ and $\bar{x}_t$, respectively, from the **evidence** used to support the calculations in 9.1 and $df_{\bar{x}_c}$ and $df_{\bar{x}_t}$ are the degrees of freedom for the control and treatment groups.

Equation 5

$$\Delta_{diff} = \sqrt{\overline{DQ}.(SE_{\bar{x}_c}{}^2 + SE_{\bar{x}_t}{}^2)}$$

where $\overline{DQ}$ is the adjustment for **data quality** as calculated using Equation 6 , and $SE_{\bar{x}_c}$ and $SE_{\bar{x}_t}$ are as previously described.

Equation 6

$$\overline{DQ} = \frac{\sum_{i=1}^{n} D_i + S_i + T_i + G_i}{n \times 4}$$

where D_i, S_i, T_i and G_i are the **data quality** scores for data source, system likeness, temporality and geography, respectively, taken from APPENDIX , for the data representing the i^{th} variable used to calculate the emissions from the **GHG** source nominated in section 5.1.2 using a CF calculator, and n is the number of variables that are used to calculate the **GHG emissions** from the nominated **GHG** source.

9.2.2 REGRESSION APPROACH

A regression approach refers to the prediction of an **emissions reduction** using an equation that is developed using statistical analysis. When a regression approach is used to estimate the **emissions reduction** associated with the implementation of a **technology**, the **claimable emissions reduction** shall be calculated using the appropriate equation below. Equations rely on the calculation of a **prediction interval**, and the method to calculate the **prediction interval** is dependent on characteristics of the equation (*e.g.* the numbers of dependent variables in the equation) that is used as a basis for calculations, and it is the responsibility of the biometrician supporting the protocol user to determine the most appropriate approach to calculating the **prediction interval**.

Case 1 - Regression equation for a change in emissions relative to a control expressed as a negative decimal or percentage.

Equation 7

$$GHG_{adj_{t(0.6)}} = \frac{\hat{y}_{adj}}{r\%} + 1$$

Where the dependent variable is a negative value expressing the change in emissions relative to a control (*e.g.* a 60% reduction in **GHG emissions** is represented by the value of -60), then $GHG_{adj_{t(0.6)}}$ shall be calculated using Equation 7. Where $\hat{y}_{adj}$ is the relevant **prediction interval** calculated using the critical value from the t-distribution for the relevant df and a 60% confidence level, adjusted for **data quality**, and $r_{\%}$ is 100 convert $GHG_{adj_{t(0.6)}}$ to a decimal format where $\hat{y}$ is a percentage or 1 in all other instances. Where Equation 7 is used to calculate $GHG_{adj_{t(0.6)}}$ the **prediction interval** that results in a value for $\hat{y}_{adj}$ being greater than the value for $\hat{y}$ shall be used.

Case 2 - Regression equation for a change in emissions relative to a control as a positive decimal or percentage.

Equation 8

$$GHG_{adj_{t(0.6)}} = 1 - \frac{\hat{y}_{adj}}{r\%}$$

Where the dependent variable is a positive value expressing the change in emissions relative to a control (e.g. a 60% reduction in **GHG emissions** is represented by the value of 60), then $GHG_{adj_{t(0.6)}}$ shall be calculated using Equation 8 where $\hat{y}_{adj}$ is the relevant **prediction interval** calculated using the critical value from the t-distribution for the relevant df and a 60% confidence level adjusted for **data quality** and $r_{\%}$ is 100 convert $GHG_{adj_{t(0.6)}}$ to a decimal format where $\hat{y}$ is a percentage or 1 in all other instances. Where Equation 8 is used to calculate $GHG_{adj_{t(0.6)}}$ the **prediction interval** that results in a value for $\hat{y}_{adj}$ being less than the value for $\hat{y}$ shall be used.

*Case 3 - Regression equation for **GHG** emitted relative to a control expressed as a decimal or a percentage.*

Equation 9

$$GHG_{adj_{t(0.6)}} = \frac{\hat{y}_{adj}}{r\%}$$

Where the dependent variable expresses the **GHG** emitted relative to a control (*i.e.* a 60% reduction in **GHG emissions** is represented by the value of 40) then $GHG_{adj_{t(0.6)}}$ shall be calculated using Equation 9 where $\hat{y}_{adj}$ is the relevant **prediction interval** calculated using the critical value from the t-distribution for the relevant df and a 60% confidence level adjusted for **data quality** and $r_{\%}$ is 100 convert $GHG_{adj_{t(0.6)}}$ to a decimal format where $\hat{y}$ is a percentage or 1 in all other instances. For Equation 9, the **prediction interval** that results in a value for $\hat{y}_{adj}$ being greater than the value for $\hat{y}$ shall be used.

Equation 10

$$DQ_i = \frac{D_i + S_i + T_i + G_i}{4}$$

where D_i, S_i, T_i and G_i are the **data quality** scores for data source, system likeness, temporality and geography, respectively, taken from APPENDIX B for the i^{th} variable used to populate the regression equation.

Where the approach allows for the **data quality** adjustment to be made for each variable then the **data quality** for each variable shall be calculated using Equation 10 and applied to each variable within the square root function of Δ_t, otherwise the average **data quality** (Equation 6) shall be calculated and applied within the square root function of Δ_t (as demonstrated in APPENDIX D).

9.2.3 NON-PARAMETRIC STATISTICAL ASSESSMENT

Where the reduction in **GHG emissions** associated with the implementation of a **technology** was assessed using non-parametric statistical methods, the use of the results from that analysis as a basis for calculating a claimable **GHG emissions reduction** is permitted. The calculation of a claimable **GHG emissions reduction** shall be done by a qualified statistician and shall use an approach that adjusts a mean effect by the specified probability of exceedance, appropriately adjusted for DQ.

9.3 FREQUENCY OF CALCULATION

The calculation shall be reviewed annually, when data used to calculate a **claimable emissions reduction** changes or when experimental results that improve the robustness of the adjustment factor are made available via publication in a relevant scientific journal (see section 7.2).

10 MULTIPLE TECHNOLOGIES

Where multiple technologies are implemented within the same system and each **technology** reduces a different emissions source, then the protocol shall be applied to each **technology** individually and each **GHG emissions** source adjusted using the relevant protocol output. Where multiple technologies are implemented within the same system and the technologies reduce the same emissions source, then sections 5 to 7 shall be completed for each **technology**. Sections 8 and 9 shall be completed for the technologies combined (*i.e.* the **evidence** used to calculate **GHG emissions reduction** shall be from experiments that implemented technologies simultaneously).

11 REPORT

To ensure transparency, a report shall be generated that provides the required information as outlined in sections 5 to 9, with the headings of each section corresponding to those used in this document. Example reports are presented in APPENDIX C and APPENDIX D. The information provided shall be suited for the intended use of the protocol outputs. For example, the worked examples presented are for a single dairy, with the system description providing detail for that dairy, however, where the protocol is used by a dairy processor, the system description would be a description of all the dairies that supply the dairy processor. Similarly, where the protocol is integrated into a CF calculator used by a dairy processor, a value for $GHG_{adj_{t(0.6)}}$ would not be presented as is done for the worked examples, because the values for $\hat{y}$ and $\overline{DQ}$ will be different for each supplier that is analysed. In such a case, the report would provide the equation used to calculate $GHG_{adj_{t(0.6)}}$ and include any values (*e.g.* $t_{(0.6,df)}$) that are calculated using the **evidence** provided in 9.1.

For transparency, where the $GHG_{adj_{t(0.6)}}$ is incorporated in a CF calculator/calculation, the developer of the CF calculator shall make the report available to the reviewer of the CF calculator/calculation.

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APPENDIX A

[Final flow chart to be included here.]

APPENDIX B

DATA QUALITY MATRIX

Data quality category	Description	DQ
Data source	Directly measured	1
	Calculated data based on measurements	1.5
	Calculated data based partly on assumptions	2.5
	Qualified **estimation** (by experts)	5
	Non-qualified **estimation**	Not acceptable
System likeness	Data are from the system being assessed by the protocol	1
	Data are from a system or systems with a key variable[+] +/- 5% of the system being assessed by the protocol	1.5
	Data are from a system or systems with a key variable[+] +/- 10% of the system being assessed by the protocol	2
	Data are from a system or systems with a key variable[+] +/- 20% of the system being assessed by the protocol	4
	Data are from a system with unknown key parameters[+]	Not acceptable
Temporal	Less than 1 years old	1
	1 – < 3 years old	2.5
	3 - <6 years old	4
	More than 6 years old	Not acceptable
Geographical	Data from the exact system being assessed by the protocol (location specific)	1
	Data from the same region as the system being assessed	2
	Data from a region with similar production conditions	5
	Data from a region with somewhat similar production conditions	10
	Data from unknown region or region with distinctly different production conditions	Not acceptable

+ a key variable is a defining variable for a dairy system (e.g. FPCM output (kg/hd/day, cow number)

APPENDIX C

WORKED EXAMPLE FOR CALCIUM CYANIMIDE ($CaCN_2$)

Preface

*This worked example demonstrates the application of the protocol to the use of calcium cyanimide to reduce CH_4 emissions from an anaerobic effluent pond with the data from a relevant publication used to calculate $GHG_{adj_{t(0.6)}}$. Based on current available **evidence**, **GHG emissions reduction**s associated with the use of calcium cyanimide could not be claimed under the protocol. The reasons for this are:*

1. *The use of $CaCN_2$ does not have regulatory approval in the jurisdiction in which the dairy system being assessed is located.*
2. *There is no full life cycle assessment of $CaCN_2$ production and use available*
3. *Only one **piece of evidence** to support the efficacy of $CaCN_2$ in reducing CH_4 emissions from effluent ponds is available (a minimum of 3 are required)*
4. *The **experiment** was done in a laboratory setting and there is no **evidence** that the results from this setting were transferable to an effluent pond in a commercial dairy.*
5. *There was no available **evidence** to demonstrate that the efficacy of the $CaCN_2$ in reducing **methane** emissions was consistent for longer time periods, particularly across seasonal conditions.*

*This worked example therefore not only demonstrates how the requirements set out in the protocol are applied to the **evidence** that demonstrates the efficacy of a **technology** but also how the equations in the protocol are applied to calculate $GHG_{adj_{t(0.6)}}$.*

*This **technology** also has the potential to change to N_2O emissions from manure and claimed improvements in fertiliser quality of applied manure would have further impacts on mitigation potential. There are no available data to incorporate these factors into the example and, therefore, they are not addressed further here. A full **LCA** of the product is likely to generate different climate change benefits than those calculated by the protocol due to the inclusion of the N_2O emissions.*

1 TECHNOLOGY AND IMPLEMENTATION CONTEXT

1.1 SCOPE

1.1.1 TECHNOLOGY

The product is a chemical named calcium cyanamide ($CaCN_2$). Its CAS number is 156-62-7.

1.1.2 USE

Calcium cyanimide was included in slurry to reduce CH_4 emissions from the effluent system and will be used throughout the entire year. As per recommendations from the manufacturer of the proprietary product Eminex, 1 kg of $CaCN_2$ was added for each m^3 of slurry in the pit, with applications repeated every 6 weeks. Recommendations for use of the proprietary product Eminex can be found online at https://www.alzchem.com/en/brands/eminex/#accordion-3472-item-3.

1.1.3 SYSTEM

This application of the protocol was specific to the use of $CaCN_2$ in a commercial dairy that was also used for research and educational purposes. The dairy was located in northern Victoria, Australia and receives an average annual rainfall of 556 mm, most of which falls in winter. The region has a Mediterranean climate with hot, dry summers and cool winters. The soils were variable and include loams and clay. The dairy was predominantly a pasture-based system with some supplementation 9 months a year and a total mixed ration supplied for 3 months (summer). It was a self-replacing system and over the year there was an average of 285 Holstein-Friesian dairy cattle.

The dairy produced an estimated 109 tonnes of milk solids in 2021 with cows averaging 6,669 litres of FPCM per lactation. The diet of milkers was comprised of pasture and pellets year-round and high protein hay in spring and summer and silage in autumn and winter. Non-milkers were fed pasture and cereal hay in spring with pellets added in autumn and winter. Slurry was collected from the milking parlour and the barn where animals are housed in the summer, and stored in an anaerobic lagoon with a volume of 10,980m^3. The pond was cleaned out every 4 months.

The efficacy of the **technology** was assumed to be breed, age and weight independent.

1.1.4 IMPLEMENTATION PERIOD

Calcium cyanamide was applied to all the manure generated by the animals during the summer period.

2 SAFETY

2.1 REGULATORY APPROVALS

Calcium cyanimide did not have approval in the jurisdiction of the assessed system. This means $CaCN_2$ did not meet the criteria set out in the protocol however it will be used as a **technology** to demonstrate the application of the protocol.

It has been approved and available for use in Germany and Austria since late 2021. It is rolling out to wider markets in the EU.

2.2 ENVIRONMENTAL IMPACTS

No full life cycle assessment has been performed on Calcium cyanimide. This means $CaCN_2$ did not meet the criteria set out in the protocol. However, it will be used as a **technology** to demonstrate the application of the protocol.

A CF of the product Perlka, a $CaCN_2$ fertiliser, was completed by Dekra. This product had a CF of 2,225 kg CO_2e per tonne of Perlka. As part of this analysis the effectiveness of $CaCN_2$ as a manure **methane** inhibitor was tested. The emissions associated with the production and degradation of the $CaCN_2$ product was 27.4 kg CO_2e/m^3 treated effluent and this resulted in an 87% reduction in emissions compared to the reference case where no $CaCN_2$ was applied (Schindler, 2021)

Calcium cyanimide is associated with other environmental impacts and results from other areas of concern have not been published. It has been used as to sterilise soil and on its own has been restricted for use as a fertiliser. This is in part due to risks posed to surface water and soils (see here). The extent of these risks in the **context** of use as a manure additive needs to be addressed with a full **LCA**.

*------------Mock example only – no actual **LCA** undertaken as yet---------*

*An **LCA** was undertaken on manure treatment with and without $CaCN_2$ for a dairy production system at a rate of 1 kilogram per cubic meter of effluent being processed in anaerobic pond system and then land applied.*

*The **LCA** showed that the Climate change benefits are 20% higher than those calculated via the protocol as the **LCA** included benefits of reduced nitrous oxide as well as lower **methane** emissions. The addition of calcium cyanimide to manure treatment leads to 12-fold increase in freshwater ecotoxicity results of manure treatment process, which translates into a 10% increase to the freshwater ecotoxicity results for milk utilizing this **technology**. All other indicators showed very little variation between the system with and without the $CaCN_2$ treatment.*

2.3 IMPACTS TO THE FARMING SYSTEM

Application of $CaCN_2$ has been shown to have other beneficial impacts on the farm system. The manufacturer reports that there are lower hydrogen sulphide emissions from manure with use of the product which improves worker safety. They also claim less floating layer formation and lower necessary storage volume and better fertilising effect of applying the slurry. It can be applied to the slurry without modifications to slurry storage facilities. However, workers need to be careful not to touch, breathe or ingest $CaCN_2$ and use of personal protective equipment is required. Environmental effects that could impact on farm productivity would be addressed with the required **LCA**.

The only published literature addressing the impacts of $CaCN_2$ on cattle health, welfare, productivity, or **product quality** is an article that confirms that cattle should not be directly exposed to $CaCN_2$ due to the development of dermatitis when added to the material spread on the floor (Onda, 2008). Searches of “Calcium cyanamide” AND either “animal health” “animal welfare” “milk” or “cattle” were performed in Google Scholar and Web of Science. Literature was available to support the hazards associated with inhalation and skin contact, use as a pesticide, and fertiliser but nothing else specific to impacts on dairy cows or dairy systems, and much of it decades old.

3 DEMONSTRATING EFFICACY OF TECHNOLOGY

3.1 Evidence 1

The first **piece of evidence** used to support the **GHG emissions reduction** associated with the use calcium cyanimide is Holtkamp et al. (2023). It is an open access article with the DOI 10.1016/j.wasman.2023.02.018.

The publication does not meet the requirement that experiments not be conducted in a laboratory setting however this **evidence** is included to demonstrate the application of the protocol. The publication meets the requirement with respect to journal quality. The research was published in the journal Waste Management and the article was published in 2023. A search of the Norwegian Register (results here) shows that the journal Waste Management was a level 1 journal on the register in 2023.

3.2 Evidence 2

Not applicable. (*There is only one* ***piece of evidence*** *to demonstrate confidence in calcium cyanimide as* ***GHG emissions reduction technology****. This means calcium* *cyanimide does not meet the criteria set out in the protocol however it will be used as a **technology** to demonstrate the application of the protocol.*)

3.3 Evidence 3

Not applicable.

4 DATA QUALITY

When calculating $GHG_{adj_{t(0.6)}}$ based on the difference between two means, the data that are used to calculate the **GHG emissions** for the nominated source are used to adjust the calculated **GHG emissions reduction** for **data quality**.

For this worked example, the **GHG emissions** source was **methane** from the dairy effluent pond and the calculations used to estimate these emissions in Dairy Greenhouse Gas Accounting Framework tool (Eckard, 2020) are sourced from the Australian National **GHG** Inventory using the equations below for the dairy location.

Equation C.1

$$\mathrm{I} = (1.185 + 0.00454\mathrm{W}^2 - 0.0000026\mathrm{W}^2 + 0.315LWG)^2 \times (MP \times 3.054 \div 0.6 \div (0.00795 \times DMD - 0.0014) \times 1.1$$

where I is the daily intake, W is the liveweight of animals, LWG is the liveweight gain of animals, MP is the milk production and DMD is the dry matter digestibility of the intake.

Equation C.2

$$M = (I \times (1 - DMD) + (0.04 \times I)) \times 0.0148 \times P$$

Where M is the **methane** produced, VS is the volatile solids that enter the effluent system, I is the intake per head per day, DMD is the dry matter digestibility of the daily intake and P is the proportion of manure that is diverted to the effluent system.

M is then used to calculate the total **methane** from the animals during the housed period.

Equation C.3

$$Total\ M = M \times N \times D$$

where Total M is the total **methane** emitted during the period (D) for the number of cattle (N) housed.

The variables that are required to calculate **methane** from the manure management system are those included in the equations above as presented in Table C.1.

Table C.1 Variables, their values, units, data source and the quality of data used.

Variable	Value	Unit	Data source	Data quality (A, S, T, G)
Liveweight	640	Kg	Averages calculated from measurements	1.5,1,2.5,1
Liveweight gain	0	Kg/hd/day	Calculated from measurements	1.5,1,2.5,1
Dry matter digestibility	70	%	Converted from metabolizable energy of intake	5, 4, 1, 5
Animal numbers	300	Number	Measured	1,1,2.5,1
Proportion of manure captured by effluent system	100	%	Estimated due to animals being housed	1,1,2.5,1
Milk production	25	L/hd/day	Measured	1,1,2.5,1

Animal numbers, liveweight, liveweight gain, milk production, and proportion of manure captured by the effluent system had similar **data quality** values. The values were direct measures or calculated based on measurements (Data source), came from the system being assessed (System likeness), were 2 years old (Temporal) and were from the exact system being assessed (Geographical).

Dry matter digestibility (DMD) was calculated from several data sources. The concentrations of various feed types and their DMD were based primarily on on-farm data and results of feed tests. However, pasture DMD was based on values from the Australian National Greenhouse Gas Inventory which use an estimate of DMD from a stratified random sample of Australian dairy farms published in 2012 (n=41; Christie 2012). This gave a DQ of 5 for a qualified estimate. The systems included in that analysis were quite variable in milk production giving a value of 4 for system likeness. Although the study used was over 10 years old, the data were used in the most recent National Greenhouse Gas Inventory, hence it was assumed to be less than 1 year old (T = 1) and is applicable to national level assessments (G = 5).

Data quality was calculated using Equation 6 of the protocol based on values in **Error! Reference source not found.** (Equation C.4)

Equation C.4

$$\overline{DQ} = \frac{\sum_{i=1}^{n} D_i + S_i + T_i + G_i}{n \times 4}$$

$$= \frac{(1.5+1+2.5+1) + (1.5+1+2.5+1) + (5+4+1+5) + (1+1+2.5+1) + (1+1+2.5+1) + (1+1+2.5+1)}{6 \times 4}$$

= 1.5

5 CALCULATION OF GHG EMISSIONS REDUCTION

5.1 EVIDENCE USED FOR CALCULATIONS

The publication used for calculations was Holtkamp et al. (2023) as described earlier. Standard errors were not provided in the text of the publication so were inferred from published graphs. This has been done to enable the demonstration of the application of the protocol. Use of this data in the protocol would require that standard errors of the mean values were reported in written form. The publication meets requirements for **evidence** as outlined in the previous section.

The use of $CaCN_2$ in the system being assessed (*i.e.* the $CaCN_2$ was added to slurry) was the same as that used in Holtkamp et al. (2023) and the concentration of $CaCN_2$ added was consistent with the rate applied in Holtkamp et al. (2023).

There was a lack of **evidence** to support consistent effectiveness of $CaCN_2$ across all seasons where properties of the effluent pond such as water temperature are likely to change. There was also no **evidence** to support an absence of adaptation of the microbial population to the use of $CaCN_2$. For the purposes of this worked example, it was assumed that the reductions reported in Holtkamp et al. (2023) were representative of reductions that occur year-round as long as the instructions for the product “Eminex” were followed for the entire implementation period.

The research used to support calculations is from a laboratory-based **experiment** using sealed flasks containing a litre of effluent. The application of this data to a commercial dairy effluent system cannot be justified due to differences such as the volume of the effluent, daily additions of material to the effluent pond and the change in the composition of effluent added to the system. The research was used for this worked example to demonstrate the application of the protocol.

5.2 EQUATIONS

Equations from section 9.3.1 were used to calculate $GHG_{adj_{t(0.6)}}$ for CH_4 emissions from dairy slurry in the system being assessed.

Values required to perform calculations are presented in Table C.2 below.

*Table C.2 Symbols used in equations in the protocol, their description and values for the $CaCN_2$ worked example. Values followed by * were inferred from graphs in the publication.*

Symbol	Description	Value
$\bar{x}_c$	Mean of control group	669
$\bar{x}_t$	Mean of treatment group	3
$SE_{\bar{x}}$	Standard error of control group	340*
$SE_{\bar{x}_t}$	Standard error of treatment group	1.5*
$df_{\bar{x}}$	Degrees of freedom for the control group	3
$df_{\bar{x}_t}$	Degrees of freedom for the treatment group	3
n	Number of data variables required to calculate **data quality**	6
$t_{(0.6,4)}$	Critical t-score for 60% chance of exceedance with 4 degrees of freedom	-0.27

Populating the equations from the protocol with the values from section 9.3.1 resulted in the following (note that equation number refers to the number in the protocol).

Equation C.5

$$\Delta_{diff} = \sqrt{DQ(SE_{\bar{x}_c}{}^2 + SE_{\bar{x}_t}{}^2)} = \sqrt{1.5 \times (340^2 + 1.5^2)} = 430$$

Equation C.6

$$df = \frac{(SE_{\bar{x}_c}{}^2 + SE_{\bar{x}_t}{}^2)^2}{(\frac{SE_{\bar{x}_c}{}^4}{df_{\bar{x}_c}} + \frac{SE_{\bar{x}_t}{}^4}{df_{\bar{x}_t}})} = \frac{(340^2+1.5^2)^2}{(\frac{340^4}{3} + \frac{1.5^4}{3})} = 3$$

Equation C.7

$$\bar{x}_d = \bar{x}_c - \bar{x}_t = 669 - 3 = 666$$

Results from Equation C.5 to Equation C.7 are then used to populate Equation C.8.

Equation C.8

$$x_a = \bar{x}_d + t_{(0.6,4)}.\Delta_{diff} = 666 + -0.27 \times 430 = 550$$

Finally, results from Equation C.8 are used to populate Equation C.9.

Equation C.9

$$GHG_{adj_{t(0.6)}} = \frac{\bar{x}_c - x_a}{\bar{x}} = \frac{669 - 550}{669} = 0.18$$

6 Application of $GHG_{adj_{t(0.6)}}$

Note that this section is for reference only and is not required to be included in a report produced by the use of the protocol

A CF of the system being assessed was calculated using the Dairy Greenhouse Gas Accounting Framework tool (Eckard, 2020). A total of 347 t CO_2e of **methane** were emitted by manure from cattle housed in the dairy during the summer period. Multiplying the effluent **methane** over the summer period by $GHG_{adj_{t(0.6)}}$ resulted in effluent **methane** emissions of 63 t CO_2e. The CF of the dairy can then be re-calculated by replacing the original value with the adjusted value. By subtracting the adjusted value from the original value, we can claim an **emissions reduction** of 271 t CO_2e from **methane** over the summer period when the animals were fully housed.

APPENDIX D

WORKED EXAMPLE OF PROTOCOL FOR 3- NITROOXYPROPANOL

Preface

*This worked example demonstrates the application of the protocol to the use of 3-nitrooxypropanol (3-NOP) to reduce enteric CH_4 emissions from dairy cattle, with the data from a relevant publication used to calculate $GHG_{adj_{t(0.6)}}$. Based on current available **evidence**, **GHG emissions reduction**s associated with the use of 3-NOP could not be claimed under the protocol for the system being assessed because there is no life cycle assessment compliant with requirements set out in the protocol.*

*This worked example demonstrates how the equations in the protocol are applied to calculate $GHG_{adj_{t(0.6)}}$ and also how the requirements set out in the protocol are applied to the **evidence** that demonstrates the efficacy of a **technology**.*

1 TECHNOLOGY AND IMPLEMENTATION CONTEXT

1.1 SCOPE

1.1.1 TECHNOLOGY

The product is a chemical named 3-nitrooxypropanol, or 3-NOP. Its CAS number is 100502-66-7. This is a proprietary **technology** owned by DSM, who markets the product under the name "Bovaer".

1.1.2 USE

The 3-NOP feed additive will be included in total mixed rations at a rate of 80 mg/kg DMI that will be mixed with a pre-mixed ration during manufacture. Supplementation will occur in the summer months when housed animals have ad-lib access to a total mixed ration.

1.1.3 SYSTEM

This application of the protocol was specific to the use of 3-NOP in a commercial dairy that was also used for research and educational purposes. The dairy was located in northern Victoria, Australia and receives an average annual rainfall of 556 mm, most of which falls in winter. The region has a Mediterranean climate with hot, dry summers and cool winters. The soils were variable and include loams and clay.

The dairy was predominantly a pasture-based system with some supplementation 9 months a year and a total mixed ration supplied for 3 months (summer). It was a self-replacing system and over the year there was an average of 285 Holstein-Friesian dairy cattle.

The dairy produced an estimated 109 tonnes of milk solids in 2021 with cows averaging 6,669 litres of FPCM per lactation. The diet of milkers was comprised of pasture and pellets year-round and high protein hay in spring and summer and silage in autumn and winter. Non-milkers were fed pasture and cereal hay in spring with pellets added in autumn and winter. The total mixed ration was a mix of commercial dairy pellets and pasture silage.

The **technology** was assumed to be breed independent and age and weight independent.

1.1.4 IMPLEMENTATION PERIOD

The cattle received the supplement during the 3 months of summer when they were housed.

2 SAFETY

2.1 REGULATORY APPROVALS

The use of 3-NOP has been approved in the European Union at 53 to 80 mg active substance/ kg of complete feed with 12% moisture content. It was demonstrated that 3-NOP and its metabolites had no mutagenic or genotoxic potential (Thiel, 2019b). The primary safety concern with 3-NOP is risks to the users of the product as it was considered an irritant to eyes and skin and is harmful if inhaled. To minimise these risks the additive will be available in granular form with negligible content of inhalable particles. Use of personal protective equipment is required to prevent contact with eyes or skin (2022)

In the **context** of this use, there is approval for commercial use of 3-NOP in Australia (Byrne, 2022; DSM, 2024) as long as claims of productivity or health benefits are not made.

2.2 ENVIRONMENTAL IMPACTS

The European Food Safety Authority concluded that 3-NOP does not have an adverse effect on consumer safety or the environment (2022) and there is no concern over residues being introduced to the environment or **farming system**(EFSA Panel on Additives Products or Substances used in Animal Feed (FEEDAP), 2021).

A **LCA** using data from the manufacturer (DSM) on the climate impacts of 3-NOP production was included in an unpublished analysis (Kebreab, 2021). It found that the production of and shipping of 3-NOP in California had negligible impact on the total **emissions reduction** achieved by supplementing dairy diets in California with 3-NOP. An analysis using similar methodology covering the entire US was published in 2022. Although there was large variability between regions, use of 3-NOP reduced emissions intensity (kg fat protein corrected milk) by 12%, including emissions associated with production and transport of feed additives (Uddin et al 2022). However, a complete **LCA** of 3-NOP production including all impact categories has not been done. Therefore, 3-NOP does not comply with the protocol. Nevertheless, we have continued to work through the protocol using 3-NOP for the purposes of providing a complete example.

A **LCA** of 3-NOP would require impact results based on APPENDIX E.

It expected that the interpretation of the **LCA** might be something like.

------------*Mock example only – no actual **LCA** undertaken as yet*---------

*An **LCA** was undertaken on Milk production with and without 3-NOP for a generic production system in Europe and it shows that the Climate change benefits calculated in the **LCA** are slightly higher than those calculated via the protocol due to the **conservative data quality** corrections included in the protocol. There was no significant change in eutrophication, water scarcity, land use or soil quality impact. The resource depletion (fossil fuels) is 3% higher for the system using 3-NOP due to manufacturing impacts of the supplement.*

2.3 IMPACTS TO THE FARMING SYSTEM

There have been several studies that investigate the impact of 3-NOP on milk production, composition, and quality. Less published information is available on factors specific to animal health or welfare.

The literature summarised was found through searching Google Scholar and Web of Science for the terms (3-NOP and milk quality) or (3-NOP AND dairy AND either health, welfare OR production).

Published literature has shown no or minor effects on productivity . Several studies show no impact on DMI or milk production(van Gastelen, 2020; Van Wesemael, 2019). There is some **evidence** for decreases in milk yield (Maigaard et al 2024) which has been observed in animals on a higher 3-NOP dose (60 vs 80 mg/kg DM) (van Gastelen et al., 2022) and dairy cows on high concentrate diets (Schilde, 2021b).

In terms of composition and quality, 3-NOP is metabolised into endogenous compounds and presence of exogenous residues in the milk is unlikely. (Thiel, 2019a). An increase in milk fat has been observed (van Gastelen et al., 2022) but this is not consistent across studies (van Gastelen, 2020; Van Wesemael, 2019). Two studies have reported a significant increase in milk urea nitrogen with the use of 3-NOP (Melgar, 2021; Schilde, 2021a), . An overview of reviewed studies focusing on dairy cows is provided in Table D.1.

Table D.1 Published studies on 3-NOP and the impacts on dairy cattle welfare, feed intake/efficiency, milk production and/or milk composition.

Citation	Health/ Welfare topics	Intake/ Feed efficiency	Milk production	Milk composition/ quality
Garcia et al. (2022)	shifted rumen fermentation from acetate to propionate			
Jayanegara et al. (2018)	decreased total VFA concentration in the rumen	No impacts on DMI	Decrease in milk production (not statistically significant)	No change
Kim et al. (2020)	Decreased % acetate and increase in valerate in rumen	No change in DMI	Decrease in milk production (not statistically significant)	Increase milk fat and protein (not statistically significant)
Kjeldsen et al. (2023)	VFA concentrations in the rumen negatively affected, decreased acetate, & increased concentrations of several alcohols in the rumen.	Decrease in DMI (11%)	--	--
Maigaard et al. (2023)	--	Decrease in DMI (13%)	Decrease in ECM (9% in)	--
Melgar et al. (2020a)	No change in weight, condition, hormones except a decrease in insulin, no impact on postpartum resumption of ovarian activity	No change (as % body mass), no change in feed efficiency	No change in milk or ECM	Only an increase in short-chain fatty acids, no change in sensory properties of milk or cheese

Melgar (2021)	--	No change in feed efficiency	No change in milk or ECM yields	Increased milk fat and milk urea N concentration
Melgar et al. (2020b)	--	No change in DMI	No change in milk yield	Increase in fat concentration , *tend* to increase milk urea N
Schilde (2021a)	No changes to rumen pH but 3-NOP with high concentrated diet had a more propionic-metabolic profile	--	Decrease in ECM in cows on high concentrate diet, not in other cows	Milk lactose and milk urea increased
Schilde et al. (2022)	3-NOP improved the energy budget of dairy cows; no effect on lipomobilization in adipose deposits, and lower serum non-esterified fatty acid conc.			
van Gastelen (2020)	Increased digestibility of several nutrients, animals on 3-NOP gained more weight	No change in DMI or feed efficiency,	No change in milk yield	Addresses impacts on several fatty acids. Overall no change in milk composition.
van Gastelen et al. (2022)	--	Decrease in DMI, no change in feed efficiency	Depended on 3NOP dose. No change in milk yield with 60 mg 3NOP/ kg of DM, decline with 80 mg 3NOP/ kg DM	Depended on 3NOP dose. No change with 60 mg 3NOP/ kg of DM, decline in major components with 80 mg 3NOP/ kg DM

Van Wesemael et al. (2019)	--	No change in DMI	No change in milk yield	No change in composition

The European Food Safety Authority concluded that 3-NOP consumption does not have an adverse effect on dairy cows (European Union, 2022). Trials in beef feedstock observed animal using the DART system and found no evidence of welfare impacts (Alemu et al., 2021). Similar animal welfare information for dairy systems is has not been published. More information on the potential impacts of 3-NOP on the rumen of dairy cows is available (Pitta, 2022; Schilde, 2021b).

3 DEMONSTRATING CONFIDENCE IN TECHNOLOGY

*Under the requirements of the protocol, only one **piece of evidence** is required to demonstrate confidence in the efficacy of 3-NOP when the **piece of evidence** is a **meta-analysis**.*

3.1 Evidence 1

Meta analysis undertaken by Kebreab et al. (2023) which assessed the reduction in **enteric methane** associated with feeding 3-NOP. The studies that were included in the analysis by Kebreab et al. (2023) were not conducted in commercial or research dairies. They were appropriate studies to demonstrate confidence in this **technology** because measuring **enteric methane** accurately requires animals are housed in respiration chambers.

The publication was published in the Journal of Diary Science in 2023, that was a Level 2 journal on the Norwegian Register For Scientific Journals, Series and Publishers at the time of publication. This was demonstrated at this link.

All studies used included in the **meta-analysis** had controls groups.

Kebreab et al. (2023) is an open-access publication with a DOI of 10.3168/jds.2022-22211.

4 DATA QUALITY

Table D.2 Variables and their units, data source and the quality of data used.

Variable	**Value**	**Unit**	**Data source**	**Average data quality (D, S, T, G)**
3-NOP	80	mg/kg DM	Feed supplier	1.00 (1,1,1,1)
Crude fat	27.1	% DM	Estimated from feed tests	1.13 (1,1.5,1,1)
NDF	26.5	% DM	Estimated from feed tests	1.13 (1,1.5,1,1)
Starch	2.8	% DM	Estimated from research article	2 (1,1,4,1)

For **context**, 3-NOP intake was based on the average concentration in the purchased ration, crude fat and NDF intake were based on quality assessments of the feeds in the ration and the starch content of the feeds was obtained from published literature. Thus starch content has the lowest **data quality** rating used for the **data quality** assessment.

Data quality was calculated using Equation 6 of the protocol based on values in Table D.2.

Equation D.1

$$\overline{DQ} = \frac{\sum_{i=1}^{n} D_i + S_i + T_i + G_i}{n \times 4}$$

$$= \frac{(1+1+1+1) + (1.5+1+1+1) + (1.5+1+1+1) + (1+1+4+1)}{4 \times 4}$$

= 1.3

5 CALCULATION OF GHG EMISSIONS REDUCTION

5.1 EVIDENCE USED FOR CALCULATIONS

The **evidence** used for calculations is the equation developed using meta-regression published by Kebreab et al. (2023) with a DOI of 10.3168/jds.2022-22211.

Kebreab et al. (2023) did not address the duration of the effectiveness of 3-NOP when fed continuously. Studies of 3-NOP have reported different responses between species of ruminal methanogen (Duin et al., 2016; Pitta et al., 2021) and **evidence** (Vyas et al., 2018) suggesting that over time the rumen adapts to 3-NOP and the dominant species of methanogens changes. This can lead to a reduction in the efficacy of 3-NOP in reducing **enteric methane**. Research has yet to determine the factors that regulate rumen adaptation to 3-NOP and **enteric methane** emissions increase relative to the start of 3-NOP use. However, a study (Schilde, 2021a) has demonstrated that rumen adaptation in dairy cattle did not occur over a 148 day period of feeding. The period for which 3-NOP was fed to dairy cattle was summer in Australia (*i.e.* December – February), a total of 90 days, was less than the 148 days in (Schilde, 2021a) so a reduction in enteric CH_4 reduction was claimed for the entire duration of animals being housed.

Kebreab et al. (2023) is a **meta-analysis** that examined the reduction in **enteric methane** associated with 3-NOP used in barn-housed total mixed ration systems in different locations. The system being assessed is barn-housed during the summer period where animals are fed a total mixed ration so **emissions reduction**s could only be claimed for that period as Kebreab et al. (2023) was not relevant to pasture-based production.

The studies used in the **meta-analysis** used animal chambers or sulphur hexafluoride to estimate **enteric methane** emissions from animals. The known relationship between intake and **enteric methane** provides confidence that the results from the experiments used in the **meta-analysis** are relevant to a commercial dairy. As such, there was a high degree of confidence that the equation from Kebreab et al. (2023) would be suitable to estimate reduction in **enteric methane** when implemented in the system being assessed here.

5.2 EQUATIONS

Kebreab et al. (2023) conducted a meta-regression to examine relationships between feed quality variables, 3-NOP and CH_4 yield and then used leave-one-out cross validation (LOOCV) to determine the model that explained the most variation.

The equation from Kebreab et al. (2023) used to calculate $\hat{y}$ for the calculation of a **prediction interval** was;

Equation D.2

Δ CH_4 yield (%) = −30.8 − 0.226 × (3-NOP − 70.5) + 0.906 × (NDF − 32.9) + 3.871 × (crude fat − 4.2) − 0.337 × (starch − 21.1)

= −30.8 − 0.226 × (80 − 70.5) + 0.906 × (26.5 − 32.9) + 3.871 × (2.8 − 4.2) − 0.337 × (27.1 − 21.1)

= -46.2

where 3-NOP = 3-nitroxypropanol dose (mg/kg of DM), and NDF, crude fat, and starch are in % DM.

Equation D.3

$$PI = \hat{y} \pm t_{1-\alpha,k-2} \cdot \sqrt{MSE(1 + \mathrm{x}^{\mathrm{T}}(\mathrm{X}^{\mathrm{T}}\mathrm{X})^{-1}\mathrm{x})}$$

is the equation to calculate **prediction interval**s for multiple linear regression developed using a meta-regression analysis where $t_{1-\alpha,k-2}$ is the critical t-score for the relevant α with k cases, MSE is the mean square error of the regression equation, x and X are matrices of the values that are used to populate the equation to calculate $\hat{y}$ and the design matrix of the regression equation, respectively, and x^T and X^T are x and X transposed.

Equation D.4

$$PI = \hat{y} \pm t_{1-\alpha,k-2}. RMSE$$

Equation D.5

$$\hat{y}_{adj} = \hat{y} \pm t_{1-\alpha,k-2}. \overline{DQ}. RMSE$$

Kebreab et al. (2023) did not report **prediction interval**s from the LOOCV and the design matrix of the regression equation was not available, however Kebreab et al. (2023) did report the RMSE of Equation D.2 developed using the LOOCV analysis. Hence, it was not possible to use Equation D.3 to calculate the prediction interval and instead Equation D.4, that is generally regarded as being suitable to calculate a **prediction interval**, was used as the basis for calculating the **prediction interval**. Integrating the **data quality** adjustment into Equation D.4**Error! Reference source not found.** resulted in Equation D.5.

Equation D.6

$$GHG_{adj_{t(0.6)}} = \frac{\hat{y}_{adj}}{r\%} + 1 = \frac{\hat{y} \pm t_{1-\alpha,k-2}.\overline{DQ}.RMSE}{100} + 1 = \frac{-46.2 \pm 0.256 \times \sqrt{1.3 \times 51.1}}{100} + 1$$

Equation D.7

$$GHG_{adj_{t(0.6)}} = \frac{(-44.1, -48.3)}{100} + 1$$

Equation D.8

$$GHG_{adj_{t(0.6)}} = \frac{-44.1}{100} + 1 = 0.56$$

The dependent variable of the equation from Kebreab et al. (2023) was an **emissions reduction** relative to a control and a negative value (*i.e.* the unadjusted value for $\hat{y}$ of -46.1 indicated that **enteric methane** emissions would be 53.8% lower than a control treatment based on the data used to populate **Error! Reference source not found.**), hence the appropriate equation to calculate $GHG_{adj_{t(0.6)}}$ from the protocol was Equation 7.

Equation D.6 shows Equation 7 of the protocol populated with the relevant equation for $\hat{y}_{adj}$ and populated with the relevant critical t-score, RMSE from Kebreab et al. (2023) and **data quality**, as calculated above. Populating Equation D.6 resulted in two values for $\hat{y}_{adj}$ (Equation D.7) and, consistent with section 9.2.2 of the protocol that states the **prediction interval** that results in a value for $\hat{y}_{adj}$ being greater than the value for $\hat{y}$ shall be used, a value of -44.1 was chosen that resulted in a $GHG_{adj_{t(0.6)}}$ of 0.56 (Equation D.8).

6 Application of $GHG_{adj_{t(0.6)}}$

Note that this section is for reference only and is not required to be included in a report produced by the use of the protocol

A CF of the dairy under study was calculated using the Dairy Greenhouse Gas Accounting Framework tool (Eckard, 2020). A baseline total of 6 454 kg CO_2-e of **enteric methane** were emitted by dairy cows housed in the dairy during the summer period. When 3-NOP was fed to these animals that resulted in **enteric methane** emissions of 3 614 kg CO_2-e. The CF of the dairy production can be recalculated by replacing the baseline value of 6 454 kg CO_2-e with 3 614 kg CO_2-e for **enteric methane**. Subtracting the adjusted **GHG emissions** for **enteric methane** from the baseline **enteric methane** value gives a claimable **GHG emissions reduction** of 2840 kg CO_2-e.

APPENDIX E

*Table E.1 Impact categories recommended for the **LCA**. Other impact categories should be used where they are relevant to the **technology**.*

Impact category	Recommended method	Rationale
Climate change	**IPCC GWP** 100 AR6 or more recent updates	The basis of the **GHG abatement**
Resource use- fossil	Frischknecht et al. (2003) or similar	Production energy requirement for the supplement
Ozone depletion potential	Chanin et al. (1999)	Included due to ozone depleting impact of bromoform (CH_3Br)
Freshwater Eutrophication	Payen et al. (2021)	Growing *Asparagopsis* to produce a bromoform based **enteric methane** inhibitor may involve emission of nutrient rich water from growing systems
Water scarcity	Boulay et al. (2018)	Changes in productivity are possible which may affect water embodied in feed production.
Land use impacts on ecosystem services	Brandão et al. (2011) or similar	Changes in productivity are possible which may affect land demand for feed. .
Ecotoxicity and Human toxicity	Fantke et al. (2021)	Bromoform has a freshwater ecotoxicity effect and CF value for human toxicity – non cancer.

APPENDIX F

[RECOMMENDATIONS FOR FUTURE RESEARCH AND USERS OF PROTOCOL – TO B E COMPLETED**]**