Description of the Agrosfär model

– a tool for the climate impact assessment of farms, crop and animal production systems in Sweden

Version 1.1
Farm perspective and crop,
milk and beef products

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Europeiska jordbruksfonden för landsbygdsutveckling. Europa investerar i landsbygdsområden

Foreword

Agrosfär is an EIP-Agri financed project aimed at developing a software solution that can calculate climate footprints on a detailed level within primary food production in Swedish Agriculture. This report describes an updated version of the climate calculation model used in the software solution, Agrosfär. Agrosfär is based on automatically generated data from the Agronod platform, which retrieves data from the farm's various systems. To some extent, data needs to be supplemented to Agrosfär to carry out a climate calculation; this data is added directly to the tool. The goal of Agrosfär is to calculate the carbon footprint of the farm and its products over time, enable benchmarks between similar farms, and visualize where climate-reduction activities will have the highest effect.

The calculation model team consisted of specialists from Lantmännen, Hushållningssällskapet, Växa and RISE with support from a project manager and a data scientist who have worked with the first version of the model between November 2021 and April 2022. The first model version was implemented in the Agrosfär software and tested by farmers in 2022. The updated version was implemented in the Agrosfär software and tested by farmers in 2023. Agrosfär has developed and been deployed to more users over time.

Maria Berglund, Hushållningssällskapet Halland, has primary responsibility for the calculation model related to animal husbandry and manure management.

Martin Laurentz, Lantmännen, has primary responsibility for the calculation model related to crop production.

The LCA-methodology of the updated report has been internally reviewed by Danira Behaderovic and Serina Ahlgren at RISE, and the animal model has been reviewed by Mikaela Lindberg at SLU.

The Agrosfär climate calculation model has gone through a third-party revision, performed by Andreas Asker and Martyna Mikusinska, LCA experts at Sweco.

Agrosfär is a product of Agronod; owned by Växa, Lantmännen, LRF, Hushållningssällskapet, Arla and HKScan.

Summary

The agricultural sector in Sweden needs to cut GHG emissions and contribute to the climate goal of net-zero emissions by 2045. The GHG reduction goal for agricultural emissions is not quantified, but the Swedish climate policy framework states that '*Swedish food production shall increase as much as possible with as little climate impact as possible'*. Multiple key actors within the sector of food and agriculture have developed roadmaps or industry specific goals for reducing GHG emissions from the sector. Consequently, requirements for transparent GHG accounting and reporting are increasing within the agricultural sector, both on a national and international level.

The purpose of the Agrosfär tool is to establish an automatic data driven climate calculator used to calculate GHG emissions from agricultural products and on a farm enterprise level. Automation and automatic data collection will save time, increase the accuracy of the calculations, and simplify updates of the tool to keep it aligned with the most recent climate data and climate reporting methodology. It will make it possible to continuously carry out follow-ups on climate performance indicators and measure improvements from climate measures taken.

A working group consisting of agricultural life cycle assessment experts has developed the framework of the tool (e.g., setting system boundaries, selecting methodologies and input data). A technical team has developed algorithms, a digital interface and coupled the tool to other existing agricultural databases, providing farm specific information on crop and animal production data, soil characteristics, carbon footprints and amounts of purchased inputs etc. The tool and user interface have been developed based on input from farmers through prototyping and in-depth interviews.

The priority guidelines on which the calculation model is based are the Product Environmental Footprint Category Rules (PEFCR), the International Dairy Federation (IDF)'s approach for carbon footprint for the dairy sector, and FAO Livestock Environmental Assessment and Performance guidelines (FAO LEAP). From the farm perspective, the Greenhouse Gas Protocol (GHG Protocol) Corporate Standard, GHG Protocol Agricultural Guidance (Scope 1 & 2) and GHG Protocol Corporate value chain (Scope 3) Accounting and Reporting Standard are guiding standards. Where standards have diverged or where assumptions have been required, the working group has made expert judgements on which method/guideline to follow or what assumptions to make.

A first version of the tool, first described in report version 1, was developed as the basis for further development. The first version contains an animal and a crop module, and can calculate the carbon footprint of crops, milk and beef. This report (version 1.1) has been updated to include the most recent developments of the tool. The main change is that the tool can now also be used to calculate farm climate impact on a yearly basis. Future possibilities to develop the tool and calculation model are described in chapter 7, including suggestions for developing modules for more animal production types, deepening the integration between the crop and animal modules, expanding sources for automatic data collection, developing a carbon sequestration module, and other

technical and methodological improvements to ensure alignment with important climate reporting standards.

The report will be repeatedly updated as the tool develops, and new versions of the tool are released.

Sammanfattning

Jordbrukssektorn i Sverige behöver minska utsläppen av växthusgaser och bidra till klimatmålet om nettonollutsläpp till 2045. Målet för minskning av växthusgasutsläppen för jordbrukets utsläpp är inte kvantifierat, men det svenska klimatpolitiska ramverket säger att 'den svenska livsmedelsproduktionen ska öka så mycket som möjligt med så liten klimatpåverkan som möjligt' och flera nyckelaktörer inom livsmedels- och jordbrukssektorn har tagit fram färdplaner eller branschspecifika mål för att minska utsläppen av växthusgaser från sektorn. Följaktligen ökar kraven på transparent redovisning och rapportering av växthusgaser inom jordbrukssektorn, både på nationell och internationell nivå.

Syftet med verktyget Agrosfär är att skapa en automatiserad, datadriven klimatberäkning som kan användas inom svenskt lantbruk för att beräkna växthusgasutsläpp på produkt- och gårdsnivå. Den automatiserade datainsamlingen sparar tid, ökar noggrannheten i beräkningarna och förenklar uppdateringar av verktyget över tid för att ligga i linje med de senaste klimatrapporteringsmetoderna. Det ska vara möjligt att kontinuerligt göra uppföljningar av nyckeltal och mäta förbättringar från vidtagna klimatåtgärder.

En arbetsgrupp bestående av experter på livscykelanalys inom jordbruket har tagit fram beräkningsmodellen för verktyget, dvs har satt systemgränser, valt metoder, emissionsberäkningar och emissionsfaktorer. Ett tekniskt team har utvecklat algoritmerna, ett digitalt gränssnitt och integrerat verktyget till befintliga jordbruksdatabaser som tillhandahåller gårdsspecifik information om grödor, djurproduktionsdata, markegenskaper, och inköpta varor etc. Verktyget och användargränssnittet har utvecklats baserat på input och feedback från referenslantbrukare genom prototyper, test och djupintervjuer.

Prioriterade riktlinjer som beräkningen av klimatpåverkan från produkter är baserad på är Product Environmental Footprint Category Rules (PEFCR), International Dairy Federation (IDF) tillvägagångssätt för koldioxidavtryck för mejerisektorn och FAO Livestock Environmental Assessment and Performance Guidelines (FAO LEAP). För gårdsperspektivet är Greenhouse Gas Protocol (GHG Protocol) Corporate Standard, GHG Protocol Agricultural Guidance (Scope 1 & 2) och GHG Protocol Corporate value chain (Scope 3) Accounting and Reporting Standard vägledande. Där standarder har avvikit eller där antaganden har krävts har arbetsgruppen gjort expertbedömningar om vilken metod/riktlinje som ska följas eller vilka antaganden som ska göras.

En första version av verktyget, ursprungligen beskriven i första versionen av rapporten, togs fram som en bas för vidare utveckling. Den förta versionen innehåller en nöt- och växtmodul och kan beräkna koldioxidavtryck från grödor, mjölk och nötkött. Denna rapport, version 1.1, har uppdaterats för att inkludera den senaste utvecklingen av verktyget. Den huvudsakliga förändringen är att verktyget nu också kan användas för att beräkna klimatpåverkan från en gård på årlig basis. Framtida utvecklingsmöjligheter för verktyget och beräkningsmodellen beskrivs i kapitel 7 och innefattar bland annat att

utveckla moduler för fler djurslag, fördjupa integrationen mellan växt- och nötmodulerna, utöka antalet datakällor för automatisk datainsamling, utveckla en kolinlagringsmodul och justeringar för att säkerställa framtida anpassningar till viktiga klimatrapporteringsstandarder.

Rapporten som beskriver beräkningsmodellen kommer att uppdateras när verktyget utvecklas och nya versioner av verktyget släpps.

Content

1 Introduction

To combat climate change, all sectors need to minimise their climate impact. In order for agriculture to do so, adequate climate calculation tools highlighting hotspots in the production systems are needed. Agricultural climate calculation tools in Sweden already exist; however, these are based on the manual inputting of data.

The goal with Agrosfär is to establish a full suit automatic climate calculator that can be used in Swedish agriculture. This will lay the foundation for efficient, data-driven farm level emission reduction, as well as providing the food industry with updated climate impact data. The system automatically collects data and structures it in a predefined framework. With a climate algorithm, the data is turned into comparable climate key performance indicators and figures which can be used as a foundation for continuous improvements, in sustainability reporting and as underlying facts in consumer communication. The results are visualised in a digital interface that farmers and farmer partners can leverage to gain a deeper understanding of the farm footprint, as well as provide a foundation for decision making.

The Agrosfär version described here is an updated version described in Ahlgren et al. (2022). The current version has the following main features:

- It covers crop, milk and beef production.
- Climate impact calculations can be done on a farm level (divided into scopes according to the GHG protocol) or on a product level.

In the construction of the model, several methodological choices must be made. The project group has discussed the methods and assumptions in regular meetings throughout the project. Support in decisions has also come from reviewing standards and guidelines for life cycle assessments (LCA), as well as scientific literature. As this is the second version of a very comprehensive model, not all sources of emissions and not all the most detailed methods have been incorporated. Areas for further development are described in chapter 7.

1.1 Aim and scope of the report

This report aims to describe the Agrosfär model “behind the scenes”. That is the methods and algorithms applied, and the scope of the model. Chapter 2 covers the general framework of the model, regarding common methods and guidelines applied, and the scope of the model. Chapter 3-6 detail the two sub-models developed on crop production and animal production, respectively. The equations implemented in Agrosfär are described in the appendixes.

Hence, this report does not cover the design of the Agrosfär model, including data collecting sheets that farmers answer or how the results are presented to farmers and end-users. In addition, this report does not describe results (i.e., the carbon footprint of products produced or total GHG emissions of enterprises) obtained from the Agrosfär model. As a consequence, part of the guidelines and LCA standards applied are not applicable for the full scope of the report, such as in the case of the completeness of inventories and activity data, as this will vary for the individual farmers. The Agrosfär model is a model, and not a complete LCA or carbon footprint report.

The target group for this report are people interested in the methods applied in Agrosfär and the status of the Agrosfär model. The report is not aimed as a guide for users of the Agrosfär model or as a means of interpretting the results of the Agrosfär model.

2 Methods

2.1 General description of model

The Agrosfär model builds on two sub models: a crop production model, and an animal production model (Figure 1).

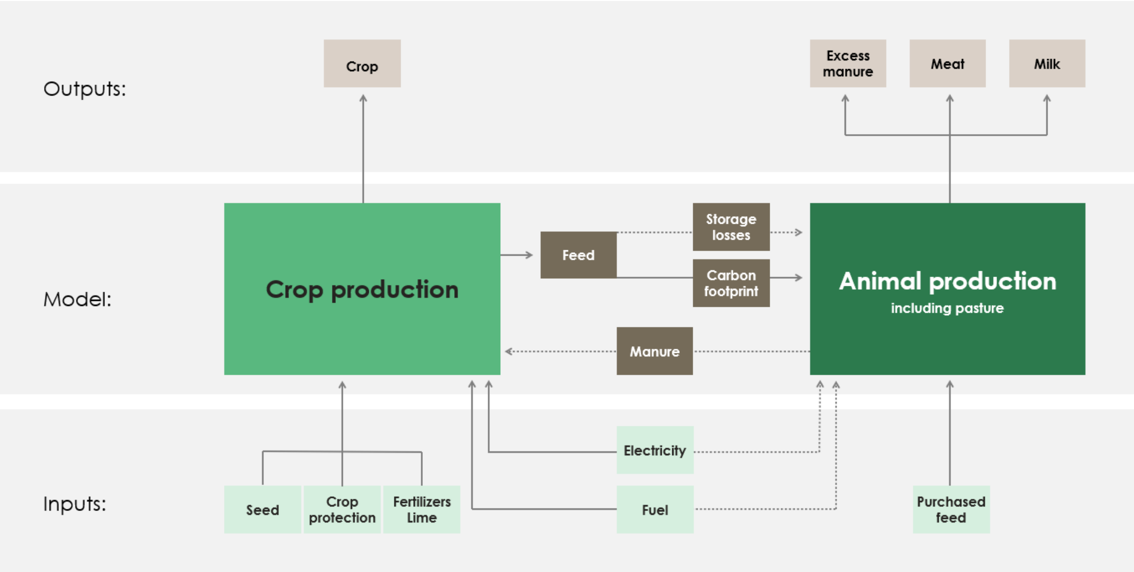

Figure 1. Schematic description of the Agrosfär model, showing the inputs and outputs of the model, and flows between the crop and animal production sub models. The flows represented by the dotted lines are not implemented in the current version of Agrosfär.

The two sub models will be connected, but in the current model there are no connections between the two sub models when it comes to the calculation of the carbon footprint of products. In the following development of the Agrosfär model, connection will be made between, for example, on-farm feed production, manure, fuel and electricity. See further description in chapter 7.

Some processes belong clearly to one sub model. For example, seeds belong to crop production and methane from enteric fermentation belongs to the animal production sub model. However, there are other processes that needs to be defined. In Agrosfär, the drying of cereals is part of the crop production sub model. Pasture and related emissions are part of animal production. Manure is part of animal production up to storage, while loading and spreading is part of crop production. Fuel (diesel, biofuels) and electricity is used in both crop and animal production. The farmer is able to fill in bought fuel and electricity as a total or by use, and the model can then subtract the energy use in crop production (registered through automatic data collection in farm machinery), making it possible to allocate the remaining part to animal production. In the current version, energy use is not allocated to the animal production when calculating product footprint, but only used when calculating the total farm emissions (see chapter 2.3).

The time aspect in modelling is of course relevant; feed is grown before it is fed to the animals. The crop for feeding the animals in a certain year has often been harvested in the previous year, but this might also happen several years before. Likewise, manure is produced in one year and spread in the next year. The Agrosfär model has a product focus and a farm focus. The product focus means that we calculate the climate impact of producing a certain amount of crops or a certain amount of milk and meat. In this case, the year the feed is produced is less important; the emissions from feed production will be included in the meat carbon footprint. The current version the Agrosfär model has been expanded, so that it can calculate the climate impact from a farm in one (calendar or other) year (see chapter 2.3).

Resulting GHG emissions calculated in the model can be extracted in several formats: for crop production, per hectare, per kg dry matter crop, per kg crop with defined moisture content, for animal production per kg ECM milk, and per kg carcass weight of beef. It can be extracted in total, or by scope according to the GHG protocol, for the total production at the farm during a year.

2.2 General description of calculation procedure

In general, emissions are counted as an **activity** * **emission factor**. For certain processes, this is done in several steps, for example the methane emissions from manure storage builds on several parameters, such as the excretion rate and the methane conversion factor. Emission factors can also be based on previous LCAs, for example the model contains emission factors for purchased feed; here the activity data could be x kg of feed, and the emission factor y kg CO_2-eq. per kg feed.

The general idea with the Agrosfär model is that activity data is collected automatically from databases which the farmers choose to connect to the Agrosfär calculation tool. The following datasets and databases can be connected initially:

- Dataväxt – Provider of digital systems for crop production
- MinGård and Kokontrollen – Journal system and data on cattle provided by the advisory service company Växa
- Markkartering – Field mapping service provided by the advisory service company Hushållningssällskapet
- LM2 – product information from orderings of, for example, feed from Lantmännen

Data from these sources is automatically collected and used to calculate emissions; however, they are validated both by manual inspection by the farmer and, long term, by automatic procedures designed to catch erroneous data.

It is not always the case that the farmer is using these databases. Additionally, not all of the data required by the climate calculations is available from these databases. In those cases, activity data can be manually entered to Agrosfär. Further, non-activity data, such as information on manure management systems, is also collected manually in most cases.

When data is manually entered to Agrosfär, there are cases where the farmer may not know all the details required. An example of this would be if the farmer does not know the crude fat content of a feed concentrate used. In these cases, it is possible to fill in blanks with standard values, either by replacing the incomplete product with a generic non-branded version, or by making inferences from other product parameters.

After the data is collected, emissions are calculated. In general, all relevant and available historical data is used when applicable, regardless of the period for which emissions are calculated. This ensures that no important data is missed. For instance, if a cow becomes pregnant during the preceding period, or if a liming agent was used several years ago, the resulting emissions are then displayed and stored, and grouped by emission source, scope and product.

2.3 Farm and product perspective

In Agrosfär, emissions can be aggregated and presented both on a product level and a farm level. This means that the result can be presented as the climate impact/kg product or as the total climate impact from the reporting company/farm for a chosen year.

The total climate impact on a farm level is essentially the sum of the climate impact of crop production and animal husbandry, but with three important differences.

The first difference is that the farm perspective includes activities taking place under a specific calendar year, while the crop production calculation covers a crop year, i.e., starting with field preparation and ending with harvest.

The second difference is that the farm level calculation may include more energy consumption than the sum of crop production and animal husbandry. The farm climate impact includes all energy consumed at the farm during the year, while crop production only includes energy use that can be attributed to field operations and drying. The current version of Agrosfär does not yet attribute any energy use to the animal products.

The third difference is that the climate impact at the farm level can be displayed according to the scopes defined in the GHG Protocol.

2.4 Emission sources covered in the model

The main greenhouse gas emissions covered in the Agrosfär model are summarised in table 2 below. Emissions of the main agricultural greenhouse gases are included: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). On farms, HFCs may be present in, for example, milk cooling equipment; these HFCs will be added in next version of Agrosfär. SF6, PFCs and NF3 are not commonly used on farms but may be present in some input materials in very low quantities; the impact of this is considered negligible.

For each activity generating an emission the following meta-data is assigned:

- Year
- Emission source
- Scope and category according to the GHG protocol
- Greenhouse gas

Table 2. Summary of main emissions included in the Agrosfär tool.

	Emission source	**Description**	**GHG**	**GHG protocol scope**
Crop production	Production of inputs	Production of fertilisers, seed, pesticides, lime, fuel and other inputs used in crop production.	CO_2, N_2O	3.1
	Use of fertilisers	Direct and indirect emissions from soil after application.	N_2O	1
	Use of manure and other organic fertilisers	Direct and indirect emissions from soil application.	N_2O	1
	Crop residues	Direct and indirect emissions from nitrogen turnover in soil, and from above and below ground crop residues left in field, including straw.	N_2O	1
	Organic soils	Emissions from organic matter oxidation when cultivating organic soils.	CO_2, N_2O	1
	Cover crops and green manure	Direct and indirect emissions from nitrogen turn over in soil after green manure or cover crop.	N_2O	1

	Emission source	Description	GHG	GHG protocol scope
	Liming	Emissions from the application of lime.	CO_2	1
Animal production	Feed production	Emissions from the production of purchased feed.	CO_2	3.1
	Enteric fermentation	Emissions from enteric fermentation in ruminants.	CH_4	1
	Manure management	Emissions from the housing and storage of manure.	CH_4, N_2O	1
	Other inputs	Acids for silage.	CO_2	3.1
Energy	Fuel use at farm	Field operations, total on-farm fuel use.	CO_2	1 and 3.3
	Fuel use during outsourced on-farm activities	Field operations, total on-farm fuel use.	CO_2	3.1 3
	Electricity use	Grain drying, heating, on farm processes (milking, irrigation, and others).	CO_2	2 and 3.3
	Heat use	Grain drying, heating of stables.	CO_2	1, 2 and 3.3

2.5 Standards and guidelines for the farm

The GHG protocol Corporate Standard and GHG Protocol Agricultural Guidance (Scope 1 & 2) have been guiding standards when calculating emissions for farms. For scope 3, the GHG Protocol Corporate value chain (Scope 3) Accounting and Reporting Standard has been the guide for those upstream scope 3 categories that Agrosfär calculates today. More emissions and categories will be included in future versions of Agrosfär (see chapter 7). Agrosfär does not calculate downstream scope 3 emissions as the calculation ends at the farm gate.

The GHG protocol divides emissions depending on whether they are direct or indirect from the company's perspective (Figure 2). Scope 1 emissions include direct emissions from sources that are controlled by the company. Scope 2 include direct emissions that occurs during the generation of purchased energy consumed by the company. Finally, scope 3 emissions include all emissions occurring from upstream or downstream activities. Scope 3 emissions are further divided into 15 categories. The current Agrosfär version includes scope 1, scope 2 and the most important upstream scope 3 emissions in 3.1, and 3.3 (see table 1 and 2). Scope 3 emissions can be summarised by category in the Agrosfär tool. Downstream scope 3 emissions will not be included in Agrosfär as the calculation model ends at the farm gate.

The operational control approach has been used when setting organizational boundaries for the reporting company/farm. Defining the consolidation approach is one of the requirements in the Greenhouse Gas Protocol. The Operational control approach means that a company accounts for 100 percent of the GHG emissions from operations over which it has control, i.e., where the company/farm can implement its operating policies (The Greenhouse Gas Protocol). Agrosfär calculates GHG emissions arising from the farm, constituting Aktiebolag (AB) or Enskilda firmor, or a combination thereof. When ownership of an Enskild firma or Aktiebolag is shared, the Operational control approach is applied.

Leasing of land is common for Swedish farms. In the Agrosfär model, the emissions from leased land is accounted to the leaseholder, not to the owner of the land.

Contract work, for example field or road work, is accounted in Scope 1 and Scope 3.3 to the contract worker, and in Scope 3.1 to the buyer of contracting services.

For more information on how Agrosfär complies with the GHG protocol Corporate Standard, GHG Protocol Agricultural Guidance (Scope 1 & 2) and GHG Protocol Corporate value chain (Scope 3) Accounting and Reporting Standard, see Appendix 1.

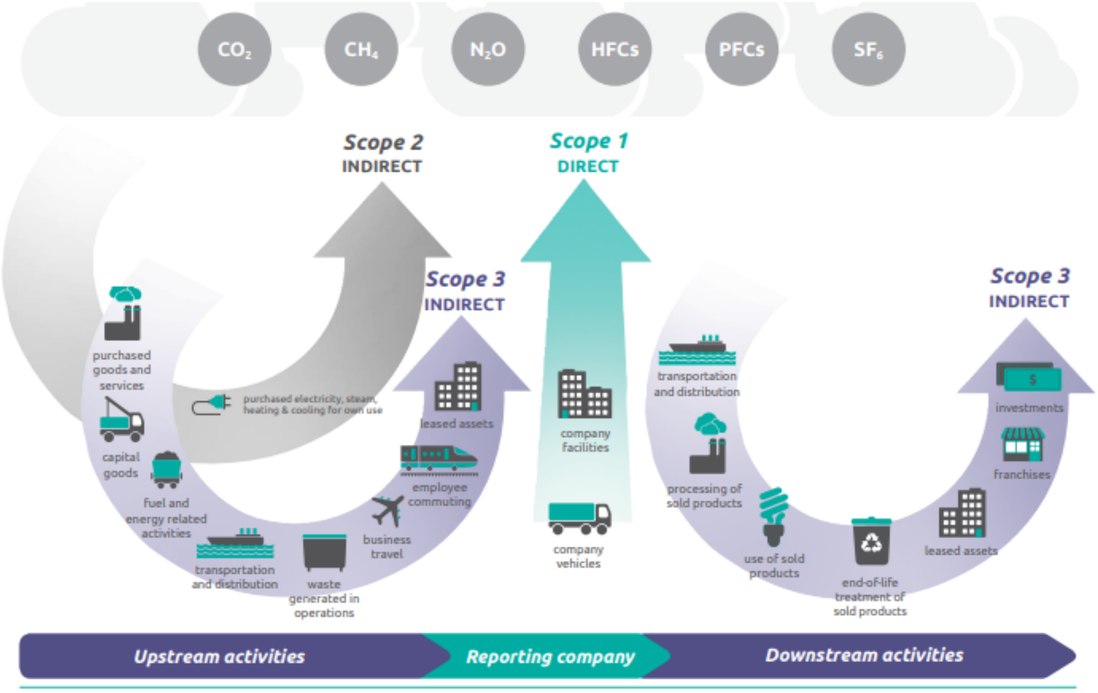

Figure 2. Illustration of GHG Protocol scopes. *Source: Greenhouse Gas Protocol - Corporate Value Chain (Scope 3) Accounting and Reporting Standard.*

Table 1. Scope 3 categories included in Agrosfär.

Scope 3 Category no.	**Included in Agrosfär**	**Reason for exclusion**
1. Purchased goods and services	Partially (see table 2)	The largest emitters, except purchased animals, are included in Agrosfär. Products such as plastics for bailing and more bedding materials will be added in next versions of Agrosfär.
2. Capital goods	No	The climate emissions for capital goods is a small share of total emissions at the farm. Capital goods may be included in later versions of Agrosfär.
3. Fuel- and energy-related activities	Yes	
4. Upstream transportation and distribution	No	The climate emissions for upstream transportation and distribution is a small share of total emissions on the farm. Upstream

Scope 3 Category no.	**Included in Agrosfär**	**Reason for exclusion**
		transportation may be included in later versions of Agrosfär.
5. Waste generated in operations	No	The climate emissions for waste are a small share of total emissions on the farm. Waste may be included in later versions of Agrosfär.
6. Business travel	No	The climate emissions for business travel are negligible compared to total emissions on the farm.
7. Employee commuting	No	The climate emissions for employee commuting are negligible compared to total emissions on the farm.
8. Upstream leased assets	No	The climate emissions for upstream leased assets are a small share of total emissions on the farm and only applicable for some farms.
9. Downstream transportation and distribution	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Downstream transportation and distribution emissions are small compared to total emissions on the farm.
10. Processing of sold products	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Emissions from the processing of sold products are small compared to emissions on the farm.
11. Use of sold products	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Emissions from the use of sold products are small compared to total emissions on the farm.
12. End-of-life treatment of sold products	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Emissions from end-of-life-treatment of sold products are small compared to total emissions on the farm.
13. Downstream leased assets	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Emissions from downstream leased assets are small compared to total emissions on the farm, and only applicable for some farms.

Scope 3 Category no.	Included in Agrosfär	Reason for exclusion
14. Franchises	NA	
15. Investments	No	Agrosfär calculates climate emissions on the farm up to the farm gate. Emissions from investments are generally small compared to total emissions on the farm.

2.6 Standards and guidelines for products

In the development of the Agrosfär model, we have consulted several Life Cycle Assessment (LCA) standards to guide methodological choices. It was not possible to fully follow one standard, as the standards have different foci. In other words, the standards complement each other. In some cases, the standards are contradictory; in these cases, we have had discussions in the project group to reach consensus. Furthermore, in some cases, there are Swedish guidelines which are not developed for the purpose of LCAs, for example, the Swedish NIR (National Inventory Report, which is the climate reporting for the Kyoto protocol) (Naturvårdsverket, 2021a, 2021b), but which are sometimes referred to and recommended to follow by LCA standards. In the Agrosfär tool, the prioritised standards are PEFCR and FAO LEAP.

The Product Environmental Footprint (PEF) is an LCA based method to quantify the environmental impacts of products, developed in an initiative by the European commission. It builds on existing approaches and international standards, such as the ISO 14040-series (International organization for standardization, ISO, 2018). PEF has also developed category specific rules, PEFCR (European Commission, 2018). The PEFCR is an attempt to converge already existing standards into one standard for various product categories. PEFCRs are being incorporated and are indicative for businesses and actors within the EU, declaring product environmental footprints, making these guidelines important for the Agrosfär tool.

FAO LEAP (Livestock Environmental Assessment Performance) is an initiative within the Food and Agriculture Organisation of the UN (FAO), providing internationally harmonised guidance and methodology for assessing the environmental performance of livestock supply chains (Food and Agriculture Organization of the United Nations (FAO), 2016). FAO LEAP provides several guidelines, and in the Agrosfär tool, two guidelines have been of certain importance: Environmental performance of animal feeds supply chains and Environmental performance of large ruminant supply chains. The FAO LEAP guidelines follow the structure of ISO 14040:2006 on the four life cycle stages of LCA.

They give guidance on data inventory, system boundaries, time boundaries for data and allocation procedures. PEF frequently refers to the FAO LEAP guidelines.

Several other important guidelines/databases follow the FAO LEAP and EU-PEF guidelines, including the GFLI (Global metrics for sustainable feed) (Global Metrics for Sustainable Feed (GFLI), 2020) and RKFS (the Swedish rules for calculating the carbon footprint of feed and grains (Foder och Spannmål, 2022).

Many of the guidelines lean on IPCC methods for estimating emissions for each greenhouse gas from different processes. IPCC does not provide guidance on how to calculate product environmental footprints, rather it gives guidance on how to calculate certain emissions, such as N2O emissions from soil (Gavrilova et al., 2019), or methane emissions from enteric fermentation (Hergoualc'h et al., 2019). The IPCC methods are divided into three different Tiers. Each tier represents a level of methodological complexity:

- Tier 1 = The basic method, simple methods based on default factors
- Tier 2 = The intermediate level, where country specific or local values should be used to obtain country specific values.
- Tier 3 = The nationally adopted model.

Decision trees are provided by the IPCC to support the decision of what Tier level is appropriate to use, and different levels can be mixed within the same report. In the Swedish national inventory reports to UNFCCC, tier 1 is used for enteric fermentation for sheep, whereas tier 3 is used for enteric fermentation for dairy cows. Different guidelines usually recommend specific tiers or minimum tiers for calculating emissions from different processes (Table 3 and Table 4).

Table 3. The most important method choices in crop production sub model.

Process	GHG	Method in Agrosfär	Guideline recommendation
Output	N/A	kg dry mass/ha and kg wet weight/ha. Mass of co-products (straw) is calculated.	According to PEFCR Feed, the following outputs per ha shall be provided: Main crop product and Co-product(s) (mass, DM, financial value, gross energy content), Residual materials that remain on the field or in soil (mass, DM).
Time boundary for data	N/A	Data for one cropping year will be used initially but in future, as data is collected for more years, an assessment periods of 3 years will be enabled.	PEFCR: For annual crops, an assessment period of at least three years shall be used (to level out differences).
Direct nitrous oxide	N2O	IPCC 2019 Tier 1, table 11.1 aggregated emission factors. 1% of N applied to soil (kg N2O-N/kg N).	PEFCR (2018). PEFCR recommends using IPCC 2006 Tier 1 (De Klein et al., 2006) or better data.

Process	GHG	Method in Agrosfär	Guideline recommendation
(N2O) to air			
Indirect N2O due to N volatilisation	N2O	IPCC 2019 Tier 2, table 11.3. For manure application, N volatilisation specific Swedish EFs are applied based on Karlsson & Rhode (2002). The EFs consider timing, spreading technique and how fast manure is incorporated into soil after spreading.	PEFCR (2018). PEFCR recommends using IPCC 2006 Tier 1 or better data.
Indirect N2O due to N leaching	N2O	IPCC 2019 Tier 2, table 11.3. 1,1 % of N2O-N of leached N. Leaching of N is calculated according to the Swedish model, based on data and models developed by Aronsson & Torstensson (2004).	PEFCR (2018). PEFCR recommends using IPCC 2006 Tier 1 or better data.
Nitrogen content crop residues	N2O	IPCC 2019 Tier 1, table 11.1A. Level of crop reside removal is either calculated as a Yes/No question (Yes = 50% of crop residues are considered removed; No =0% crop residues are considered removed) or are stated as a field specific figure if known.	PEFCR (2018). N input from crop residues that stay on the field. Kg/ha and N content.
Direct N2O emissions from organic soils	N2O	IPCC 2013 Wetlands supplement. For grassland IPCC 2013, emission factors for forestland are applied as Swedish grasslands are more like forestland than grasslands in Europe.	Compliant with PEFCR dairy. PEFCR (2018) doesn't mention N2O emissions for peat soils.
Peat oxidation	CO_2	IPCC Tier 1 reworked by Lindgren and Lundblad (2014)	Compliant with PEFCR dairy.
Carbon in urea	CO_2	IPCC 2019 Tier 1. Ch 11.4. 0,73 kg CO_2/kg urea	PEFCR (2018). CO_2 to air (from urea and urea-compounds application).
Lime application	CO_2	IPCC 2006 Tier 1. Divided by years in which lime is expected to have an effect.	Compliant with FAO LEAP: EFs for CO_2 emissions from lime application shall be

Process	GHG	Method in Agrosfär	Guideline recommendation
			taken from IPCC (2006), Volume 4, 5 Chapter 11.
Land use change (LUC)	CO_2, N2O-biogenic	Only included from purchased feed (depending on if included in source of LCI data)	FAO LEAP/PEFCR: LUC should be reported separately.
Land use (LU)	CO_2-biogenic	Not included in current version.	FAO LEAP/PEFCR: C from soil due to land use shall be included and reported separately.
Fuel combustion	CO_2	Fuel use is collected either as total farm fuel consumption or liter/ha. Data might also be collected by machinery computers tracking fuel consumption	PEFCR: field operations through total fuel consumption or through inputs of sub-farm units.
Pesticides	CO_2, N2O	Data on active ingredient/ha is collected and multiplied by EF.	PEFCR (2018). Pesticide emissions shall be modelled as specific active ingredients.
Drying and storage	CO_2	Energy use for drying is estimated either by farm data or by using standard values for used energy per kg water dried.	PEFCR (2018). Drying and storage shall always be included.
Seed input	CO_2, N2O	Information on seed input as kg/ha and total area is collected.	PEFCR (2018). Input of seed material (kg/ha) shall be collected.
Fertiliser input	CO_2, N2O	Type of fertiliser, amount of fertiliser (kg/ha) and N, P and K content is collected. EFs from fertiliser Europe are applied.	FAO LEAP: LCI data for production can be obtained from suppliers if available or can be collected from secondary databases.
Capital goods	CO_2	Not included in the current version of Agrosfär.	FAO LEAP: Capital goods with a lifetime greater than one year may be excluded; production and maintenance of machinery used in cultivation should be included. According to ISO and PEFCR, dairy capital goods can be excluded.

Table 4. Most important method choices in animal production sub model.

Process	**GHG**	**Method in Agrosfär**	**Guideline recommendation**
Animal energy requirements	Input to GHG calculations below	The method used in Norfor, i.e., another Tier 3 method than the one used in NIR.	FAO LEAP: Country-specific model used in NIR for the country in question, or alternative models which are peer reviewed, published, and are appropriate for the country in question.
Feed amounts consumed	CO_2, N2O	Based on known feed inputs, assumed feed losses and calculated energy requirements, amounts of remaining feed inputs are calculated.	FAO LEAP: Feed consumption may be calculated from energy requirements. PEFCR: NIR should guide country-specific modelling.
Feed losses	CO_2, N2O	Assumptions made for proportions of uneaten feed. Storage losses and losses due to, for example, mold were not included in the current version of Agrosfär.	FAO LEAP: Feed losses have to be included.
Enteric fermentation	CH4	Country-specific calculation method according to Swedish NIR (corresponding to IPCC Tier 3).	FAO LEAP, IDF and PEFCR: minimum IPCC Tier 2.
Excreted amounts and amounts of N	Input to GHG calculations below	The method used in Norfor, i.e., another Tier 3 method than the one used in NIR.	FAO LEAP: IPCC Tier 2
Manure in stable and storage	CH4	Calculation method according to IPCC Tier 2 based on data/emission factors from Swedish NIR and from Norfor or IPCC.	FAO LEAP: IPCC Tier 2, with use of country-specific data and EFs according to NIR.
Manure in stable and storage	Direct N2O	Based on excreted amounts of N. Emission factors from NIR, according to IPCC Tier 1.	FAO LEAP: IPCC Tier 1
Manure in stable, storage and pasture	Indirect N2O	Emissions of NH_3 estimated based on national data. After this, the IPCC Tier 1 emission factor was used to calculate the conversion to N_2O.	FAO LEAP: IPCC Tier 1
Manure dropped on pasture	CH4, N2O	Use of IPCC Tier 2; IPCC default EFs in combination	FAO LEAP: IPCC Tier 1 for N2O and Tier 2 for CH4.

Process	GHG	Method in Agrosfär	Guideline recommendation
		with country-specific activity data.	
Bedding material	CO_2, CH4, N2O	All bedding material is assumed to be straw. Bedding material is included in the calculation of emissions from manure in stable and storage. Production of straw is not included in the current version of Agrosfär.	FAO LEAP: Only straw-specific steps, e.g., harvest, bailing and transport, should be included in animal production (production up to harvest included in grain production).
Plastic for bailing of silage and straw	CO_2, CH4	Not included in the current version of Agrosfär.	FAO LEAP: All inputs should be included, but straw is not specified.
Electricity and fuel used for animal production	CO_2, CH4	In the current version of Agrosfär, all on-farm electricity and fuel use are included in the farm perspective, but not the animal production sub model or allocated between animal products.	FAO LEAP and PEFCR, in general: If possible, all inputs should be divided to reflect the actual use for different products/productions; otherwise, allocation based on physical relationship between products should be done. If that is not possible, allocation based on other relationships should be done.

2.7 Allocation procedures

The general recommendation from several guidelines is to avoid allocation, if possible, by attributing emissions as far as possible to the product generating the emissions. When not possible, for example when one process generates several outputs or when one input is used in several processes, the environmental burden (or benefit) of the input(s) must be allocated to the outputs in question. For some common processes, allocation procedures are described (e.g., allocation between milk and meat). For other processes, more general rules apply. ISO 14067 states that when allocation cannot be avoided allocation shall be done based on physical relationships between the outputs, for example based on mass, energy content or other physical relationships (International organization for standardization, ISO, 2018). When a physical relationship cannot be established, other relationships between outputs can be used, such as economic relationships (ISO 14067). The Agrosfär tool generally follows the ISO guidelines on allocation and uses specific allocation recommendations where applicable.

In the crop sub model, allocation procedures are avoided as the model is built from a field level, meaning inputs will be directly collected at field level, and emissions generated from the field are directly coupled to the crop produced at the field. The field in this case can be considered as a single production unit. In some cases, the output from one production unit might be several products, such as straw and grain. In that case, no burden from crop production is allocated to the straw, only the harvest and transportation of the straw itself. This is in line with the FAO LEAP guidelines (Food and Agriculture Organization of the United Nations (FAO), 2016).

For perennial crops which have several different life stages and where both generic and specific inputs occur at field level simultaneously, some modelling adjustments have been done to avoid allocation (more closely described in section 3.10). For green manure that generates benefits several crops ahead in the crop rotation, a custom-made solution has been developed following recommendations provided by FAO LEAP (see section 3.10).

A dairy farm produces both milk and animals for slaughter. As far as possible, activities generating emissions should be attributed to either milk or meat production. In cases where an activity is used both in milk and meat production and cannot be separated between the two, allocation is needed. For the allocation between milk and meat as products from a dairy farm, we have used the formula recommended by the IDF standard (European Dairy Association (EDA), 2018). The IDF allocation factor was originally related to the amount of milk sold, expressed as fat and protein corrected milk (FPCM). However, ECM is the dominant form used in Sweden and is used throughout the Agrosfär model. 1 kg ECM is approximately equivalent to 1.0077 kg FPCM. The empirically derived constant in the original IDF formula was 6.04. The constant was adjusted (6.04 / 1.0077 = 5.99) in the Agrosfär model to represent ECM.

$$AF_{milk} = 1 - 5.99 * \frac{M_{meat}}{M_{milk}}$$

Where:

AF_{milk} = The allocation factor for milk.

M_{meat} = The total live weight (kg per year) of animals sold for breeding or slaughter. Animals that have died on the farm are excluded from M_{meat}.

M_{milk} = The total amount of milk sold (as ECM, energy corrected milk, per year).

In this study, emissions from manure up to and including on-farm storage are included in the animal production system, while transport and emissions after application to arable land, as well as possible benefits and emissions from anaerobic fermentation or other off-farm treatments, are cut off from the animal production system. This is in line with the FAO LEAP and the PEFCR Dairy standards regarding manure with no economic value, and where no activity after storage is included in the animal production system.

2.8 Climate modelling

2.8.1 Global warming potentials

Global warming potential (GWP) is one of the most used units for expressing climate impact in LCA. Characterisation factors are used to convert the net emissions of different gases to a common indicator value, CO_2-equivalents.

Gases differ in their ability to absorb energy, that is, they have various impacts on global warming. They also differ in their atmospheric residence times. Each gas has a specific global warming potential (GWP), which allows comparisons of the amount of energy that the emissions of 1 tonne of a gas will absorb over a given time period, usually a 100-year averaging time, compared with the emissions of 1 tonne of CO_2. The IPCC publishes characterisation factors for different greenhouse gases in synthesis reports, the fifth assessment report was issued in 2013 and the sixth assessment report (The Physical Science Basis, the Working Group I) in 2021. As science progresses, the characterisation factors are modified. This is something to keep in mind when comparing LCA-results.

The chosen time horizon will influence the relative impact of different gases. Most commonly 100 years is chosen, and this is the recommended time period in most LCA-standards (ISO 14067, GHG protocols, PEF, PEFCR dairy, PEFCR feed, IDF).

For methane, IPCC publishes separate characterisation factors for fossil and biogenic emission sources. For fossil methane, the additional indirect effect from the oxidation of methane to CO_2 is included. This effect is captured to reflect the fact that methane will eventually break down to CO_2 in the atmosphere, and this CO_2 constitutes an additional burden to be attributed to the parent molecule, thus increasing the overall impact of a methane emission (Muñoz and Schmidt, 2016). Many LCA-standards (ISO 14067, GHG protocols, PEF, PEFCR dairy, PEFCR feed, IDF, GFLI) recommend the separate treatment of biogenic and fossil methane.

IPCC also gives characterisation factors with and without feedback mechanisms. Feedback mechanisms are the indirect effects of changes in climate, for example warming due to emissions of GHGs leads to an increased amount of water vapor in the atmosphere, which in turn leads to further warming. GWPs with feedback can therefore give a fuller picture of the impacts but have a higher level of uncertainty. In many LCA-standards (ISO 14067, GHG protocols, PEF, IDF), the use of GWP100 with feedback mechanisms is recommended.

In the Agrosfär model, characterisation factors for GWP100[1] are used. Assessment report 6 (AR6) IPCC 2021 is the default, with the possibility of switching to previous versions of IPCC (see Table 5). The greenhouse gases are reported separately in the model, and as total CO_2-eq.

Table 5. Characterisation factors for GWP100 are used. IPCC 2021 is the default, but the model gives the possibility to switch to previous versions of IPCC.

	AR6, IPCC 2021 (default)	**AR5, IPCC 2013 excluding cc-feedback**	**AR5, IPCC 2013 including cc-feedback**
CO_2 biogenic	0	0	0
CO_2 fossil	1	1	1
CH_4 biogenic	27.2	28	34
CH_4 fossil	29.8	30	36
N_2O	273	265	298

2.8.2 Biogenic carbon

In LCA it is often assumed that the carbon dioxide released from biogenic sources (e.g., from biomass uptake, respiration, combustion of biofuels) has no climate effect. This neutrality assumption is due to the fact that all the carbon present in biomass has been taken up during photosynthesis. However, in recent years, it has been argued that biogenic carbon should be considered in climate calculations.

The issue of biogenic carbon accounting can be divided into three categories: (1) accounting of carbon flows, (2) reporting of biogenic carbon content and (3) assessing the climate impact of carbon storage/removal.

First, some LCA-standards (ISO 14067, GHG Protocol) state that all carbon flows should be accounted for in the life cycle (Greenhouse Gas Protocol, 2011; International organization for standardization, ISO, 2018). By including, for example, the uptake of carbon from the atmosphere in crop cultivation, and release through respiration, decomposition or combustion in the same year, the climate impact will be zero. This brings its usefulness into question. Guinée et al. (2009) suggest that in LCAs of agricultural products, a distinction between "negative" and "positive" emissions may be

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[1] Allen et al (2018) have described an alternative measure, GWP*, which could be used to describe the consequences of changed emission levels of short-lived greenhouse gases related to historical or future emission levels. It can, for example, be used for evaluations of different emission scenarios based on historical and forecasted greenhouse gas emissions on a global level. The Agrosfär model calculates the static current annual emissions on a product level (and in upcoming versions, on a farm level) where GWP* is not a relevant measure (Landquist et al., 2019).

relevant information, i.e., when viewing the emissions as genuine cycles. It is important to note that some databases distinguish fossil CO_2 from biogenic CO_2, but this is far from all of them, meaning that it is a difficult task to follow these guidelines. It is therefore not included in the current version of Agrosfär.

Secondly, according to ISO 14067, reporting the biogenic carbon content is mandatory when performing cradle to gate studies, as this information may be relevant for the remaining value chain. This would, for example, imply that the carbon content of crops, milk and beef should be reported for Agrosfär. However, we see no immediate use for this type of information for the end users of Agrosfär and therefore chose not to include the carbon content of the products leaving the farm in the current version of Agrosfär.

Thirdly, removing carbon from the atmosphere for a longer period of time can have a climate impact, as can be seen with the storage of carbon in wood constructions or soil carbon build up. In ISO 14067, it is stated that if there is more than 10 years between uptake and release, the climate impact should be included but reported separately. PFCR, on the other hand, states that credits from 'temporary carbon storage' are excluded and that biogenic carbon emitted later than 100 years after its uptake is considered as permanent carbon storage. In the scientific literature, accounting for the time lag between uptake and release of biogenic carbon is an on-going debate, and especially in the bioenergy sector, opinions differ (see Matuštík & Kočí, 2022). In Agrosfär, we have not included climate impact of carbon storage in products. Storage of soil carbon (see section 2.9) is not included in the current version of the model; however, carbon release from organic soils is included (see section 3.8).

2.9 Land use and land use change

Land use change (LUC) and land use (LU) can have an impact on soil carbon stocks. Land use change refers to the transformation of one land use category to another, e.g., transforming forest to cropland or cropland to grassland. LU refers to the impact of land management practices on soil carbon stocks, through tillage, the addition of manure and crop rotation effects. A net increase of soil carbon stock is referred to as a removal of carbon from the atmosphere, whereas a net decrease of soil carbon stock is referred to as an emission. Change in soil carbon stocks is counted as biogenic carbon emissions or removals. If LUC and/or LU is included, it is often reported separately for transparency reasons.

LUC can be divided between direct land use change (dLUC) and indirect land use change (iLUC). Direct land use change occurs when non-agricultural land is converted to agricultural land for the purpose of producing an agricultural product or inputs for that agricultural product. Indirect land use change is harder to distinguish, it is described as the act of converting non-agricultural land to agricultural land through changes in agricultural practices elsewhere (European Commission, 2020).

Whether LUC or LU should be included in carbon footprint calculations varies between guidelines. According to FAO Leap, the impact of LUC is relevant to include if it occurred within 20 years of the assessment year. In cases where this is true, each year carries 5% of the total LUC induced emissions (Food and Agriculture Organization of the United Nations (FAO), 2014). Changes occurring more than 20 years ago should not be included. According to ISO 14067, LUC shall be included, whereas LU is not required (International organization for standardization, ISO, 2018). IDF (2018) recommends including LUC but not LU as changes in soil carbon under different management systems is an ongoing field of research, there is a lack of data or broadly accepted methods (European Dairy Association (EDA), 2018). PEFCR refers to FAO LEAP, which recommends including both LUC and LU, while simultaneously highlighting the complexity of modelling LU.

The calculation of soil carbon dynamics requires a large amount of data and there is yet to be a simple and mainstreamed approach. Modelling soil carbon changes due to LU requires calculation models built on long term primary data and the models should be peer-reviewed and scientifically accepted. This type of model usually requires a highly detailed level of input data to yield relevant results. Further, to be able to credit carbon removal, an assurance of permanency needs to be provided, which is a challenge in changeable systems, such as agriculture.

Due to the complexity and difficulty in modelling changes in soil carbon stocks, soil organic carbon changes caused by LU are not included in the current version of the Agrosfär tool but will be established in later versions if adequate models are developed and become acceptable within carbon accounting.

LUC is not calculated in the model for on-farm feed production. Swedish cropland has been decreasing since the 1950s and decreased by 30% during the period 1951-2015. Rather than expanding, cropland is being afforested or exploited and used for buildings, housing, and infrastructure. Land use change from the expansion of agricultural land into forestland is not relevant for Swedish conditions (Statistics Sweden, 2019). However, if including a soil carbon tool in future versions of the model, land use change will have to be considered for each farm as local farmers may have cleared pastures or trees on their land to prepare cropland.

LUC is included for purchased and imported feed depending on the source of feed data. If included, it is reported separately.

Emissions of GHG occurring from cultivation and oxidation of organic soil are included (see chapter 3).

2.10 Uncertainties

The broadly defined concept of uncertainty includes two types: uncertainty and variability. Uncertainty (sometimes called “epistemic uncertainty”) is defined as incomplete or imprecise knowledge, and can be further subdivided into parameter, model, and scenario uncertainties. This type of uncertainty arises, for example, from uncertainty in data and emission factors, the choice of model used to calculate emissions, or from the choice of system boundaries. These types of uncertainties can be reduced by increasing measurement accuracy, increasing model accuracy, and collecting data that better represent the system. Variability, on the other hand, can be defined as the inherent differences that cannot be reduced (e.g., variations in yields); it can, however, be represented more precisely if more information is available (Chen and Corson, 2014).

2.10.1 Standard recommendations

All standards taken into consideration in this project address the importance of describing confidence level and uncertainties in environmental footprint studies. The description shall follow the principles of relevance, accuracy, completeness, consistency and transparency. It should include methodological choices regarding use and end-of-life profile, allocation methods, the source of global warming potential (GWP) values used and calculation models. Assumptions should be clearly described, as should the ways these assumptions could impact the results.

Data with high uncertainty can negatively impact the overall quality of the inventory. According to PEFCR, it is required to calculate a Data Quality Requirement index to address the uncertainties regarding data quality. This index should be based on the representativeness of the analysed system, based on technology, geographical location, time and precision.

There are specific uncertainties addressed in the standards concerning the methodological choices, for example the GWPs for near term GHGs are not recommended for use. These addressed uncertainties have been taken into consideration in the methodological choices in this project.

2.10.2 Uncertainties in activity data

In the Agrosfär model, actual farm data is used to the greatest extent possible; farmers can upload their data from a number of sources but can also manually enter data. There is a risk that some numbers are wrong, or that the farmers misinterpret what data is requested. For several of the input variables, there are min/max values in the model, ensuring that unrealistic numbers cannot be entered.

2.10.3 Variations in results

It is always difficult to compare results from different climate calculation tools. Tools are developed for a specific purpose, and the methods, assumptions and input data are chosen to match the needs of the user. A tool developed for climate farm advisory services might therefore not be appropriate for use for product carbon footprinting.

Further, methods for calculations can vary depending on the detail level needed, and when it was developed. Emission factors are constantly changing as science progresses, as is the case for the characterisation factors to convert greenhouse gasses to CO_2-equivalents, or emission factors to estimate nitrous oxide emissions from fields.

In Agrosfär, a major benefit is the direct connection to farm specific data. This means that we might be able to see large variations in results between farms and between years. As the tool continues to be used, average results can be calculated over the years and results become less varied. Variations between farms can sometimes be caused by natural variability, i.e., due to inherent differences that cannot be reduced, for example, a farm can have many fields with organic soils, making it difficult to compare results between different farms.

2.10.4 Uncertainties in emission factors

There are many emission factors included in the model, related to both the crop and the animal production calculations. Some emission factors are known to have a large impact on the results while also being connected to large uncertainties, such as nitrous oxide emissions from cropping and emissions from manure deposited in pasture (Chen and Corson, 2014).

As an example of uncertainties in emission factors, a study by Flysjö et al. (2011) is of interest. They modelled a representative dairy farm in Sweden and estimated the influence of uncertainties in emission factors for enteric CH_4 emission and three N_2O emission factors. For Swedish milk, the climate impact varied between 828 and 1560 kg CO_2-eq. per 1000 kg energy-corrected milk.

The uncertainties related to emission factors may be quite large. In the current version of Agrosfär, uncertainty ranges are not included. This could however be a future development.

2.10.5 Tests and validation of model

The Agrosfär model consist of many sub models and equations. To check that the model yields accurate results, several tests were performed, and results analysed for consistency. The crop production models are based on a previously developed spreadsheet model, and several testcases could be run in both the spreadsheet and Agrosfär model to check that the results coincide. The animal model did not originate from an existing spreadsheet model and is more complex where different processes influence each other, making it difficult to check one parameter at a time in a spreadsheet. The test approach for animal production is to use test data based on one animal's lifecycle, as well as the changes in a herd over one year.

3 Crop production

3.1 Methods

The crop production model builds on an already existing tool Dataväxt (Dataväxt, 2022). Dataväxt is primarily used as a crop production support tool, where crop production data is collected on a field level. Data on a yield level, amount and type of fertiliser, manure application (timing, type of manure, nutrient content and spreading technique), seed input, application rate of pesticides, field work, preceding crop, and soil type are among the data collected. This is the foundation of the ad-on climate calculating tool. The climate calculator in Dataväxt builds on this field specific activity data and applies emission factors for calculating carbon footprints which are crop and field specific. Biogenic emissions, such as direct and indirect N_2O emissions, are calculated using the same activity data but applying equations and emission factors from IPCC. The results at the field level can be aggregated to results on a crop level, representing the average carbon footprint of each crop cultivated on the farm.

The Dataväxt model has been the foundation of the Agrosfär tool, with some modifications:

- Green manure was added
- Updated emission factors
- GHG emissions presented both on a gas level (CH_4, N_2O and fossil CO_2/biogenic CO_2) and as CO_2-eq.
- The impact on indirect N2O from N volatilisation of manure spreading technique and how fast manure is incorporated into soil after spreading are provided.

GHG emissions presented by Scope according to the GHG protocol (see section 2.3-2.4)

The calculation is performed in seven steps, described in the following chapters. All equations used in the crop production model are presented in Appendix 3.

3.2 Seed

The total climate impact from the production of used seed is calculated based on use per hectare, area and the emission factor of seed (Appendix 3, Equation 3. 1). Emission factors for seed has been estimated from the available data from life cycle analyses on cereals. For the varieties where data for seed production were lacking, the climate impact has been assumed to be 20% higher than the climate impact from the cultivation of each variety. The share of N_2O impact of total climate impact of seed production has been estimated at 40-60% of the total GWP based on grain variety.

3.3 Fertilisers and lime

The total climate impact from the production of used fertiliser and lime is calculated based on application rate per hectare, area and the emission factor of the raw materials (Appendix 3, Equation 3. 2 and Equation 3. 3).

The emission factor for mineral fertilisers have been taken from various sources:

- Specific data for the mineral fertilisers is used where the climate calculation has been made available by the manufacturer.
- When specific data did not exist, general data from (Fertilizers Europe, 2022) is used.
- For mineral fertilisers where data on %N is included, the carbon footprint has been calculated based on N content.
- If the country of manufacture is not stated in the name, the carbon footprint has been calculated assuming 70% Best Available Technique (BAT) with catalytic cleaning of N_2O during production.
- For fertiliser including N, the climate impact from N_2O and fossil CO_2 are reported separately, while the others are given as a total in kg CO_2-eq./kg.

For biofertilizers, the climate impact from the production of the raw material has not been included, instead only the average impact from energy use in production and transport is given.

For manure, no climate impact for production and storage is allocated to crop protection as this is allocated to animal husbandry.

For lime, general climate impact data from Fertilizers Europe (2022) is used. This is only reported in kg CO_2-eq./kg.

The release of CO_2 in the field when spreading lime is calculated based on the lime application rate and generic emission factors according to IPCC Tier 1 (Naturvårdsverket, 2021a) (Appendix 3, Equation 3. 4). The climate impact is distributed evenly over the number of years that the liming covers (until the next liming is needed).

3.4 Crop protection

The total climate impact from the production of used crop protection is calculated based on use per hectare, area and the emission factors of crop protection based on area of use (Appendix 3, Equation 3. 5).

Emission factors for crop protection are based on data from the Ecoinvent database (Wernet et al., 2016). Each plant protection is assigned an emission factor based on area of use.

3.5 Field work

The total climate impact from the production of fuel and emissions from fuel use in field work is calculated based on fuel consumption per hectare, area and the emission factor of fuel (well -to-wheel) (Appendix 3, Equation 3. 6).

3.6 Direct nitrous oxide emissions from mineral soils

The direct N_2O soil emissions at the farm are calculated according to Chapter 11 of the 2019 Refinement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories (Hergoualc'h et al., 2019). It is calculated as the sum of N_2O emissions arising from mineral fertilisers, manure, organic fertilisers and crop residues (Appendix 3, Equation 3. 7). The inputs for the calculation are variety of crop, harvest (yield), crop residues and applied amount of nitrogen.

The direct N_2O emissions from applied mineral and organic fertiliser are calculated using the aggregated emission factors in IPCC 2019 Tier 1 (Appendix 3, Equation 3. 8 and Equation 3. 9), with emission factors from table 11.1 (Hergoualc'h et al, 2019).

The direct N_2O emissions from above and below ground crop residues are calculated based on the amount of above and below ground crop residues, and the N content in those crop residues (Appendix 3, Equation 3. 10) using the aggregated emission factors in IPCC 2019 Tier 1, table 11.1. The amount of above ground residues are calculated using the alternative method as stated in IPCC 2019, table 11.2 (Appendix 3, Equation 3. 11). The amount of below ground residues are calculated using the ratio of below-ground biomass to above-ground biomass as given in IPCC 2019, table 11.1A (Appendix 3, Equation 3. 12). N content in crop residues was taken from IPCC 2019, table 11.1A.

3.7 Indirect nitrous oxide emissions

The calculation of indirect N_2O emissions is calculated as the sum of indirect N2O emissions caused by N leaching/runoff and indirect N_2O emissions caused by N volatilisation (Appendix 3, Equation 3. 13).

Indirect nitrous oxide emissions are calculated based on crop, municipality, soil type, nitrogen content, NH-N in manure, and the date of the application of manure, which include timing, spreading technique and how fast manure is incorporated into soil after spreading. The ploughing date after harvest and use of any catch crop is also considered. The calculation is based on the calculation methods use in the VERA tool, and the Odlingsperspektiv calculation model used by Greppa Näringen (Bertilsson and Nilsson, n.d.).

3.7.1 Indirect N_2O emissions caused by N leaching/runoff

The calculation of indirect N_2O emissions caused by N leaching/runoff is calculated based on the emission factors from IPCC 2019 table 11.3 and leaching (Appendix 3, Equation 3. 14), where the leaching is calculated based on a standard leaching and different adjustments as described below.

Standard leaching/run-off – location based

A standard N leaching/run-off is calculated based on the geography and soil type. For each field in Agrosfär, the location (municipality) and the soil type is given. The standard leaching for the municipality and soil type is taken from a table originally published in Aronsson and Torstensson (2004) (Appendix 3, Equation 3. 15).

Crop specific adjustment

An adjustment factor based on the type of crop growing in the field is calculated using a table from VERA/Odlingsperspektiv (Appendix 3, Equation 3. 16).

Reduction due to tillage strategy

The possible reduction of leaching depending on the time of the next tillage after harvest and type of crop is calculated in a table from VERA/Odlingsperspektiv (Appendix 3, Equation 3. 17).

Reduction due to catch-crop

The possible reduction of leaching created by the growing of a catch crop in the field, in relation to the tilling time, is calculated in a table from VERA/Odlingsperspektiv (Appendix 3, Equation 3. 18).

Application of manure

The possible increased leaching due to the application of manure is calculated using tables from VERA/Odlingsperspektiv based on the time of application of manure, crop type and soil type (Appendix 3, Equation 3. 19-21).

3.7.2 Indirect N_2O emissions from N volatilisation

The calculation of indirect N_2O emissions from N volatilisation is carried out in accordance with IPCC 2019 Tier 2. Ammonium volatilisation is calculated separately for N in applied mineral fertiliser and N in manure, and are then combined with the emission factor for volatilisation and redeposition from IPCC 2019 table 11.3 to calculate the N_2O emission (Appendix 3, Equation 3. 22).

Ammonium volatilisation from N in applied mineral fertiliser is calculated based on the application rate per hectare, area and the emission factor of the fertiliser (Appendix 3 Equation 3. 23). The emission factor for ammonium from mineral fertiliser is set to 1.2%, which is the average value according to Swedish NIR 2021 (Naturvårdsverket, 2021a).

Specific Swedish emission factors based on Karlsson and Rhode (2002) are used for ammonium volatilisation from N in applied manure. This model considers the manure application rate per hectare, NH-N rate in manure and the loss in spreading in relation to timing, spreading technique and how fast manure is incorporated into soil after spreading (Appendix 3, Equation 3. 24).

3.8 Greenhouse gas emissions from organic soils

Drained organic soils are a source of CO_2 and N_2O emissions due to oxidation induced by drainage. Hectares of managed or drained organic soils are multiplied by a default emission factor. In the tool, soils with mulch above 40% are considered as organic soils. The emission factors for organic soil applied in the tool are in line with the emission factors used in the Swedish national inventory (Naturvårdsverket, 2021a). The CO_2 emission factor for cropland is derived from IPCC Wetland supplement (Hiraishi et al., 2014) but have been reworked by Lindgren and Lundblad (2014) to include results only from countries with similar climatic conditions as Sweden. For N2O emissions from cropland on organic soil, the emission factor is derived from IPCC without adjustments. Emissions from pasture on organic soil is not included in this version of Agrosfär (see chapter 7.3).

The N_2O and CO_2 emissions from organic soils is calculated using Equation 3. 25, Equation 3. 26 and Equation 3. 27 in Appendix 3.

For further information on organic soils, see Appendix 2.

3.9 Crop drying

The climate impact from crop drying is included if the drying occurs on the farm. The total climate impact from drying is calculated either from measured electricity and fuel consumption in the dryer if given by the farmer (Appendix 3 Equation 3. 28), or estimated based on the standard energy consumption in drying and dry matter content in the crops before and after the drier (Appendix 3, Equation 3. 29). In both cases, the type of fuel and source of electricity is needed and in the latter case, the yield from the field/ the mass of crop dried is also needed.

Emission factors for fuel and electricity are from Energimyndigheten.

3.10 Perennial crops

Perennial crops and grass crops are crops with a life cycle spanning several years, including different life stages. The life stages can include a juvenile stage (establishment year), a period of maximum production, and a period of decline in production. Only looking at one year and field at a time will give a product with a high climate impact in the juvenile stage when production is low, and a lower climate impact when production is high. PEFCR feed and FAO LEAP recommend that all life cycle stages of a perennial crop should be included and averaged, meaning that all development stages are proportionally represented in the studied period. If the different life stages are known to be disproportional, it is recommended to make a correction by adjusting the crop areas allocated to different life stages to a theoretical steady state (European Commission, 2020; Food and Agriculture Organization of the United Nations (FAO), 2016). Assuming a steady state situation where all production stages and generic inputs are proportionally distributed will give an averaged climate impact for the output which will not differ year to year due to different life stages being overrepresented.

Solution in the Agrosfär tool: In the Agrosfär tool, all the emissions from inputs (except for field work) and biogenic emissions are divided over the lifetime of the perennial crop. If the perennial crop has a lifetime of three years, the emissions will be divided by the number of years and equally distributed over those years. Emissions from field work (the production of fuel and emissions from burning fuels) is allocated to the single field. By including all fields with perennial crops at the farm, the average will over time be close to a theoretical steady state where all production stages are represented. Each assessment year will include some fields where grass crops are established, fields with maximum production, and fields with declining production which are tilled and re-sown. The final climate impact will be an average of all the fields, thus including all the production stages.

3.11 Green manure

According to FAO LEAP feed supply chains, green manure can be categorised as a generic input and emission at the field level. It is an input which covers several production cycles and generates benefits for the whole crop rotation (i.e., not only the crop which it is sown into or before) even if the input occurs in only one year (Food and Agriculture Organization of the United Nations (FAO), 2016). This can be handled by averaging out inputs over all fields in the rotation, without considering complex bio-physical relations.

Solution in the Agrosfär tool: In the Agrosfär tool, the biogenic emissions caused by green manure are calculated based on a fictive yield, as the green manure is not harvested but instead the biomass is ploughed down in the field. Users of the tool can thus choose an option stating that the current crop is a green manure crop and that no biomass is removed from the field. The user can state a fictive yield, which is the foundation for calculating direct and indirect dinitrogen oxide emissions. The emissions are attributed to the single field where the green manure is grown, and thus allocated to the crops grown in the field over the coming years based on the number of years that the user estimates that the green manure will have a nitrogen effect (up to a maximum of five years). This approach is more appropriate than allocation of the emissions to all the crops at the farm as some crops might never benefit from the nitrogen provided by green manure.

4 Pasture

Sweden has a tradition of managing semi-natural pastures with a relatively high number of trees and bushes. Some of the typical habitats also have a low fodder value but have a high biodiversity value. As well as being very important for nature conservation, they are considered a significant and valued element of the cultural heritage in Sweden. These types of pastures are generally not fertilised or ploughed. In the Agrosfär model, the emissions caused by animal manure during grazing (CH_4, direct N_2O and indirect N_2O from ammonia emissions) on these permanent grasslands is included in the animal production model. There could be other nitrous oxide emissions, for example, from decomposition of roots or indirectly from nitrogen leaching, but as these grasslands are nutrient poor, we can expect these emissions to be very low; they are, therefore, not included in the model. Further, emissions from more carbon and nutrient rich semi-natural pastures are not included in the current version of Agrosfär.

Animals also graze on the regrowth of grasslands used for silage production. In these cases, the emissions caused by animal manure during grazing (CH_4 and direct N_2O) is included in the animal production model. As the field is used for silage, emissions from field work and nitrous oxide emissions from soil are included in the crop production model.

5 Animal husbandry

Emissions from livestock (enteric fermentation) and manure management are calculated and organised in the same way in the Agrosfär model as in the IPCCs Guidelines for Greenhouse Gas Inventory, Volume 4 Agriculture, Forestry and Other Land Use, chapter 10 (Gavrilova et al., 2019). Many LCA and CF, including the IDF guide to CF for the dairy industry, refer to the IPCC guidelines for guidance on how to calculate greenhouse gas (GHG) emissions.

Data on livestock population, including the number of heads, production level, animal weight and weight gain, and feed characteristics, is used to estimate feed requirements (net energy [MJ NE] per animal per day or year). The heavier the animal and/or higher the production level, the higher the feed requirements.

The calculated feed requirements and data on feed characteristics is then used to estimate methane emissions from enteric fermentation.

The calculated feed requirements are also used to estimate the carbon footprint of feeds used in animal production. So far, the default carbon footprints are applied for any feed, regardless of origin. Later, the crop sub model and animal production sub model will be integrated, and the calculated carbon footprint of grains and roughage grown on the farm will be transferred from the crop model to the animal production model.

Emissions from manure management are assessed based on data on feed requirements and feed characteristics, and data on current manure management systems. Data on feed characteristics and feed requirements is used to calculate the amount of nitrogen (N) and volatile solids (VS) excreted in manure. Data on N and VS content in the manure and information about the manure management system is then used to calculate N_2O and CH_4 emissions from manure management.

The results from the current Agrosfär model are presented both on a product level (kg CO2-eq per kg product) and a farm level (ton CO2-eq per year). Estimations of emissions from animal production are close to the same in both farm and product settings. The only difference between the animal farm and product setting is how the carbon footprint of feed is calculated:

- The animal product level includes the generic carbon footprint of feeds used in animal production for both purchased feed and feed produced on the farm.
- The animal farm level includes the generic carbon footprint of feeds that are purchased during the assessed year. Greenhouse gas emissions from on-farm cultivation of feed is included in the crop production sub model.

More detail on the generic carbon footprints of feeds is given in chapter 5.10.

5.1 Motives for choosing the applied methods

The IDF guidelines on carbon footprint for the dairy industry states that at least a Tier 2 approach is necessary for the assessment of enteric fermentation (6.2) (International Dairy Federation (IDF), 2015). The IPCC guidelines provide a detailed Tier 2 method to estimate energy requirement and emissions from enteric fermentation and manure management.

More advanced Tier 3-approaches for feed requirement and enteric fermentation can be found in The Swedish National Inventory Report (NIR) and the documentation of the Norfor system, the Nordic feed evaluation system (Naturvårdsverket, 2021a; Norfor, 2022; Volden, 2011).

Energy requirements of cattle

Sweden has adopted a country specific method in NIR to estimate the energy requirements for all cattle categories (Naturvårdsverket, 2021a). It is based on methods and feed evaluation that have been used in Sweden for a long time. The assumptions and methods used in NIR are presented in Bertilsson (2016). Energy requirements are calculated following Spörndly (2003), "*Blå boken*". The energy content of feed and animal requirements are expressed as MJ metabolizable energy (MJ ME). In NIR, energy intake is eventually recalculated to MJ gross energy (MJ GE) to harmonise with IPCC's reporting requirements. An advantage of the NIR method is that it has been reviewed and approved by a reputable body; any country specific methods used in NIR must be approved by UNFCCC (United Nations Framework Convention on Climate Change).

Norfor is the new feed evaluation system developed for the Nordic countries. Norfor is based on thorough research and contains many detailed estimations and equations that stem from scientific papers. The Norfor system is documented in "*Gröna boken*" (Volden, 2011), and the equations and dataset (e.g., feed tables) are continuously updated (Norfor, 2022).

An important difference between the Norfor system and *Blå boken* is that energy requirements are estimated and expressed as net energy (NE) in Norfor instead of as metabolizable energy as in NIR. Norfor is implemented in advisory tools (IndividRAM och FoderOpti), and net energy content of feeds is reported in feed analyses. However, other advisory tools/feed planning tools are still based on *Blå boken* and MJ ME.

Equations from the Norfor system are implemented in the Agrosfär model to estimate energy requirements. The main reasons for choosing the Norfor system over *Blå boken* and NIR are:

- The Norfor system is more advanced and detailed than *Blå boken*.
- The Norfor system is the new feed evaluation system that is implemented in major advisory tools (IndividRAM and FoderOpti).
- The Norfor system is updated continuously.
- Equations from Norfor can also be used to estimate excretion rates (N and VS in manure, see below), whereas estimations of energy requirements and excretion rates are not correlated in NIR.
- Norfor enables better comparability with estimations of GHG emissions in IndividRAM.

Estimates of energy requirements are heavily based on the same parameters (e.g., production level) in *Blå boken* and Norfor as in the IPCC guidelines. Hence, the same trends can be expected with any of these methods. For example, the heavier the animal and higher the weight gain, the higher the energy requirement. However, energy requirements are expressed in different units: Metabolizable energy in *Blå boken,* and Net energy in Norfor and in the IPCC guidelines. Hence, the results (MJ per animal per day) can't be compared without conversion.

Enteric fermentation of cattle

Methane from enteric fermentation of cattle is calculated using the same equations in the Agrosfär model as in NIR. Sweden has adopted a country specific method in NIR for methane from the enteric fermentation of cattle (Bertilsson, 2016). There are separate equations for cows and growing cattle. The equations implemented in NIR were previously used in Norfor. The equations in Norfor have been updated recently (Norfor, 2022).

However, the updates are not implemented in the Agrosfär model since the updated equation for growing cattle contains a parameter (rumen degraded NDF, rd_NDF) that is not readily available in the Agrosfär model. Rd_NDF is estimated based on a set of sub-equations which describe the degradation of NDF in the rumen and intestines; these require detailed information on feeds, feeding regime and animal parameters. In addition, the updated equation for growing cattle has not been approved by UNFCCC for national reporting of greenhouse gas emissions.

Manure management of cattle manure

Estimations of N and VS excretion rates from cattle are based on equations from the Norfor system (Norfor, 2022; Volden, 2011). The excretion rates are thereby correlated to the estimated energy requirements of the animals. The Norfor system is chosen over the IPCC guidelines because of its consistency with estimations of energy requirement; the Norfor system also provides a more detailed estimation of excretion rates than the IPCC guidelines Tier 2.

The Swedish NIR contains country specific methods to estimate excretion rates from cattle. However, these methods cannot be used in the Agrosfär model. In the Swedish NIR, data on N and VS content in cattle manure is provided by the Swedish Board of Agriculture. The specific data sets or equations used by the Swedish Board of Agriculture are not specified in NIR or, to our knowledge, available elsewhere publicly. In addition, the estimates of excretion rates (N and VS content in cattle manure) are not derived from the energy requirements calculated in NIR, and it seems as if these two estimations are not correlated.

For methane and direct nitrous oxide emissions from manure storage, the IPCC Tier 2 method was used. Emission factors based on country-specific data according to the Swedish NIR were used for methane from slurry, while the IPCC default emission factors were used for methane from solid manure, as well as direct nitrous oxide emissions from all types of manure. This is in accordance with the recommendations in the FAO LEAP standard.

Emission factors for ammonia (indirect nitrous oxide) comes from the advising tool VERA. VERA was developed by the Swedish Board of Agriculture/Greppa Näringen, and the tool is commonly used by advisors to assess farm-scale ammonia emissions from stable, storage and spreading of manure. The Swedish NIR contains country specific methods to assess ammonia emissions based on the national reporting of air pollutants (Naturvårdsverket, 2021a). However, the emission factors applied in NIR are not as detailed as in VERA, and they don’t reflect differences in, for example, coverage of manure storage.

5.2 Livestock population

5.2.1 Time frame and scope

The assessment comprises 1 year, from January 1 to December 31.

The assessment comprises all cattle that lived on the farm over the year, meaning all cattle that lived there for either the entirety or part of the year (e.g., calves born, and cattle slaughtered during the year).

The calculations were carried out per head and day, and the results are then aggregated as the total emission per livestock population and year.

The time frame and scope are the same, regardless of the perspective of the calculations (farm or product perspective). In the farm perspective, the results are presented as the total emissions from the farm over one year. In the product perspective, the emissions are expressed per kg of meat, which is a mix of all types of meat produced at that farm, (e.g., the meat produced at a dairy farm will be a mix of slaughtered cows and young cattle).

5.2.2 Livestock categories

The following livestock categories were applied:

- Cows:
    - **Dairy cows.** Cows that have calved at least once and are used principally for milk production. Dairy cows are further subdivided into Lactating (dairy) cows and Dry cows.
    - **Beef cows**. Cows used to produce offspring for meat.

- Growing cattle: From birth until the animal is slaughtered or the heifer calves for the first time. Growing cattle of dairy and beef breeds are not separated.
    - **Heifers**.
    - **Bulls.** Intact males. Includes growing bulls and bulls used for breeding purposes.
    - **Steers.** Castrated males. Castrated males are considered to be steers from birth although they are born as bulls. They are castrated at such a young age that this generalisation is deemed appropriate.

5.2.3 Breeds and purpose of the animal

Breed is used to determine breed-specific default values (e.g., body weight at birth and as mature) and to identify individuals as either dairy or beef cattle. A distinction between dairy and beef breeds is needed to ensure that the right coefficients are applied, for example, for the estimation of energy requirements of bulls and methane emissions from the manure from cows.

The breed of an animal can be derived from "*Min gård*" (a system provided by Växa) and/or CDB (the central register of bovine animals, administrated by the Swedish Board of Agriculture). Each breed has a unique number code in CDB (e.g., Simmental = 14). The documentation of Norfor contains default values on body weights for a variety of common breeds, but not as many breeds as in CDB. It is assumed that default body weights of breeds that are not described in Norfor can be estimated as the same as the weight of similar breeds described in Norfor. As an example, "SKB (*Svensk kullig boskap*)" is a small dairy breed that is included in CDB, but not in Norfor (2022). It is assumed that SKB is equivalent to Jersey.

However, many cattle are crossbreeds (code 99), and they can't automatically be identified as dairy or beef breeds. Additional information is needed to identify a crossbreed as dairy or beef breeds. This information can be derived manually by the farmer or, to some extent, automatically using, for example, registered milk production (see below).

Cows of some breeds are always defined as dairy cows (e.g., Jersey) or as beef cows (e.g., Highland Cattle). But the breed may not always be sufficient to determine if the cow is used for milk production or not. There are breeds mainly used for beef production, but which can be used in milk production as well (e.g., Simmental). There are cows from dairy breeds that are not milked but are used to raise calves. The following information is used to define a cow as a dairy or beef cow:

- Dairy cows are defined as cows that are milked. This is true if the milk yield is registered or the farmer states that all cows are used for milk production.
- Beef cows are defined as cows that are not milked. This is true if the milk yield is not registered or the farmer states that all cows are used for beef production.

5.2.4 General data

There are three levels of detail: Farm, Livestock category, and Individual.

5.2.4.1 The farm

There are three cattle categories in Agrosfär: Cows, heifers, and males. The user of Agrosfär has to manually indicate the cattle subcategories present on the farm. This affects how the individual cows and males are categorised:

Cows: If the user indicates that there are:

1. dairy cows but no beef cows: All cows are assumed to be categorised as dairy cows.
2. no dairy cows but beef cows: All cows are assumed to be categorised as beef cows.
3. are both dairy cows and beef cows: Cows are categorized by breed and milk production. A cow is defined as a beef cow if it is of a beef breed and there is no registration of milk yield.

- Males (bulls and steers): If the user indicates that there are:
    1. bulls but no steers: All males are assumed to be bulls.
    2. no bulls but steers: All males are assumed to be steers.

3. both bulls and steers on the farm: The farmer has to indicate how many of the males older than 12 weeks that are steers.

All female that have not calved are defined as heifer.

In addition, the following general data is provided by the farmer:

- Organic or conventional production
- Manure storage. Describes how the manure is stored, for example, the coverage of slurry manure.
- Feedstuffs. Type of feedstuffs used, the protein and energy content of some feeds, and the amount of purchased feed.

5.2.4.2 Livestock category

The following data is provided by the farmer. Data is provided per livestock category that exists on the farm.

- Housing and manure management system. Number of heads per system (e.g., loose on deep bedding, or tied up and slurry).
- Grazing period (see chapter 5.5.2).
  - Start and end of grazing period (date).
  - Dairy cows – Grazing hours per day. The duration is assumed to be 24 hours per day for any other grazing cattle category.
  - Number of grazing periods for growing bulls. As a default, all cattle older than 6 months are assumed to graze during the grazing period, as stipulated by the law. However, bulls are exempt from these requirements. Hence, the farmer has to provide this information.
- Feeding regime.

5.2.4.3 Individual

Ready input data is available from "*MinGård*" (a system provided by Växa). Eventually, further data sources can be added, for example, regarding data related to slaughter or from CDB (the central register of bovine animals, administrated by the Swedish Board of Agriculture).

MinGård contains both data that the farmer has to provided and data that is optional to register for each animal. The following mandatory data is collected per head.

- Breed
- Sex (female/male)
- Date of birth
- Arrival at the farm: Date and cause (e.g., birth, bought)
- Leaving the farm: Date and cause (e.g., slaughter, sold, death)

- Cows and heifers: Date of calving
- Dairy cows: Milk yield (kg per day)

The following data is optional to report and is imported to Agrosfär if available. Data is reported per head:

- Weight at birth (kg)
- Registered weight(s): Date and weight (kg live weight)
- Weight at slaughter (kg live weight)
- Cows and heifers: Date of insemination
- Dairy cows: Milk yield (kg per day)

The milk yield reported for dairy cows excludes milk suckled by calves.

5.2.5 Transition between animal subcategories

Housing systems and feeding regimes can differ between heifers (e.g., manure handled as deep bedding) and cows (manure handled as slurry). The emission calculations are dependent on stable systems and feeding regimes; hence, the transition must be considered.

(Replacement) heifers are categorised as “Heifers” until the day before they give birth. Thereafter, they are categorised as “dairy cows” or “beef cows”. However, in practice, replacement heifers will join the dry dairy cows pen some time before calving, and thus the distinction between heifers and cows will not be entirely correct, considering feed and manure system. It is practical to have the shift occur on the day of calving as this day is known and registered. Furthermore, the small over-estimation of manure in the heifer system and the likewise small under-estimation in the cow system will not make any substantial difference in emissions. There is also a process in which heifers acclimatise to dairy cow feed before calving, which is not accounted for with this distinction. However, in relation to total feed use, this simplification should be insignificant.

Castrated males are categorised as steers for their entire lives, although they are born as bulls. These males are assumed to be castrated at such a young age that potential differences in growth, energy requirement, etc. between intact and castrated young males is considered to be insignificant.

5.3 Energy requirements of the animals

Methane emissions from enteric fermentation and N and VS excretion rates are correlated to animal feed intake. However, detailed and accurate data on actual feed consumption is rarely available in cattle production (especially for beef cows) or for the entire year (e.g., during the grazing period). Many dairy farms have good data on the quality (energy and protein content, etc.) and consumption of concentrates (kg per cow and day), whereas the quality and consumption of roughage (silage) is not as well known.

In addition, there may be good data on feed consumption for the (lactating) cows, whereas the farmers don't plan or track feed for heifers in such detailed. Although the amount of roughage fed (kg wet weight) may be known, we would also need reliable data on feed nutritional quality (%DM, MJ and crude protein), which is less likely.

Since we can't expect consistent data (time and quality) on actual feed consumption, we need to estimate the energy requirement (MJ per head per day). The use of estimations of energy requirement over actual feed consumption is a common practice in LCA of beef and milk (Food and Agriculture Organization of the United Nations (FAO), 2016).

There are several methods/systems available to estimate feed requirement that are used to calculate emissions from enteric fermentation and manure management:

- **NorFor**/The Nordic feed evaluation system (Volden, 2011): Developed for the Nordic countries and implemented in advisory tools such as IndividRAM. IndividRAM will eventually be replaced by FoderOpti. Parts of FoderOpti have been launched, but all functions are not yet available. The Norfor system is used by Växa and Skånesemin.
- Recommendations in **SLU feed tables for ruminants** (Spörndly, 2003): Not as complex as Norfor. These recommendations have been widely used but have been replaced by the Norfor system in some major applications. The SLU feed tables are still used, for example, to estimate energy requirements in Swedish NIR and in some advisory tools that aren't based on the Norfor system.
- **IPCC guidelines**. Tier 2. Energy requirement is estimated as net energy. The equations are similar to the Norfor system but are not as complex. A major difference is that the IPCC method is developed to assess the average energy requirement per average head and year, whereas the Norfor system is per individual per day.

Energy requirements and the energy content (MJ) of feed can be expressed in different units (see Table 6). All four units are used, or have been used, to express the energy content of cattle feed and/or to calculate methane from enteric fermentation. The energy unit applied should be indicated by "MJ" followed by an abbreviation, for example, MJ ME to denote energy content expressed as metabolizable energy. However, other abbreviations can be found in texts in Swedish. As an example, "*omsättbar energi*" (metabolizable energy) can be denoted as "OE" or "ME" in texts in Swedish.

MJ ME (*MJ OE*) has long been used in Sweden to express energy content in feed for cattle, e.g., in SLU feed tables (Spörndly, 2003). MJ ME is still in use, for example, in advisory tools based on Spörndly (2003), and MJ ME per kg feed can be found in feed analyses. Net energy is used in the NorFor system for estimations of energy requirement and feed evaluation.

Table 6. Energy units to express the energy content (MJ) of feed. The examples of default values and application (current/former) relates to feed for cattle. (Bertilsson, 2016)

Energy unit	What	Where is/was it used?
Gross energy (MJ GE) /*Bruttoenergi* (MJ GE or MJ BE)	Energy released in total combustion with oxygen. Default value 18.45 MJ/kg DM feed aimed at cattle if own value is not available (Gavrilova et al, 2019)	Enteric fermentation in IPCCs guidelines and Norfor.
Digestible energy (MJ DE) /*Smältbar energi* (MJ DE or MJ SE)	GE minus faecal energy. Default: DE = 45% (e.g., poor feeds as straw) to 85% (e.g., high quality feed, such as grain) of GE	Previous calculations of methane from enteric fermentation, Sweden.
Metabolizable energy (MJ ME)/ *Omsättbar energi* (MJ ME or MJ OE)	DE minus urinary energy and methane energy. Default: ME = ca 82% of DE	Older feed evaluation systems in Sweden (Spörndly, 2003). Current Swedish NIR.
Net energy (MJ NE)/ *Nettoenergi* (MJ NE)	ME minus heat loss. NE = ca 60% of ME	Newer feed evaluation systems (Norfor) in Sweden. Energy requirement in IPCC guidelines

Assumptions:

- The Agrosfär model can't rely on access to ready data on feed consumption. Hence, energy requirements must be estimated.
- Energy requirements are estimated based on the Norfor system, and the Energy requirements are calculated as MJ NE per head per day.
- Feed intake is assumed to be the equivalent of the estimated energy requirements. In practice, feed intake can exceed estimated requirements. This assumption seems to be in line with IPCC guideline.
- Feed intake is estimated based on energy content (MJ NE) in the feed; this is referred to as the Norfor method. If MJ NE in the feed is not known, the feed intake may have been estimated based on feed digestibility (DE%) and gross energy content as described in the IPCC guidelines. However, the net energy content is known for all feeds included in the current version of Agrosfär. There are default values (MJ NE per kg) for all feeds, and the user can manually alter the energy content of concentrates and some roughage. Hence, the alternative IPCC method has not yet been implemented in Agrosfär.

The following sections give a brief description on the estimation of energy requirements for cows and growing cattle, respectively. The equations implemented in Agrosfär is described in more details in Appendix 4.

5.3.1 Dairy and beef cows

5.3.1.1 Weight and weight gain, kg

Data on weight and weight gain is needed to calculate energy requirements. It is assumed that average data on body weight of mature animals and default weight gain in young cows is appropriate and sufficient to estimate the body weight of a single cow on a single day.

The following assumptions are made regarding body weight of mature cows:

- The mature body weight of cows refers to the weight of older cows, meaning cows that gave birth for the first time more than 730 days ago.
- The Agrosfär model determines the mature body weight as the average per breed kept on the farm (kg live weight per head of breed I on the farm in the year j).
- The average mature body weight cow is estimated from slaughter data for older cows. Slaughter data is provided as kg carcass weight per head. 1 kg carcass weight is then assumed to correspond to 2 kg live weight. If slaughter data is not available, then the default values for mature body weight is derived from Norfor as kg live weight per head of breed i (Norfor, 2022).

The following assumptions are made regarding weight gain:

- Young cows (1st and 2nd lactation) gain weight, approximately 50 kg per year (Åkerlind, M. pers comm, 2022). Hence, weight gain in young cows is assumed to be 50/365 kg per day from the first day of calving and the following 730 days.
- No weight gain in older cows (i.e., more than 730 days since calving for the first time).
- Fluctuations in weight during lactation is not considered.

5.3.1.2 Energy requirement, NEL

The energy requirement is estimated based on the Norfor system (Volden, 2011). The total energy requirement for cows, NEL (MJ NE per head and day), is calculated as:

$$NEL = NEL_{maint} + NEL_{gest} + NEL_{gain} + NEL_{milk}$$

Where:

NEL_{maint} = Energy requirement for maintenance, MJ NE per cow and day (see Appendix 4, Equation 4. 2). NEL_{maint} is calculated as a function of current body weight (see above) and activity. The heavier the animal, the higher the NEL_{maint}. The more active the animal, the higher the NEL_{maint}. NEL_{maint} is assumed to be 10% higher during grazing and for loose-housed animals than for animals that are tied up. This is in line with the Norfor system.

NEL_{gest} = Energy requirement for pregnancy, MJ NE per cow and day (Appendix 4, Equation 4. 3). NEL_{gest} is calculated as a function of mature body weight (see above) and day in gestation. The higher the mature body weight, the higher the NEL_{gest}. NEL_{gest} is low in early gestation and increases gradually in the last months of gestation.

Day in gestation is determined based on the date of last insemination or date of calving. NEL_{gest} is only calculated for pregnancies that produce a fully developed calf/calves.

NEL_{gain} = Energy requirement for weight gain, MJ NE per cow and day (Appendix 4, Equation 4. 4). NEL_{gain} is calculated as a function of current body weight and weight gain (see above). The higher the weight gain, the higher the NEL_{gain}. NEL_{gain} is included for cows in their 1st and 2nd lactation. Older cows are assumed not to gain weight.

NEL_{milk} = Energy requirement for milk production, MJ NE per cow and day. Estimated as a function of daily milk yield (kg energy corrected milk, ECM). The higher the milk yield, the higher the NEL_{milk} (Appendix 4, Equation 4. 5–- Equation 4. 7). The function is linear. Hence, the annual energy requirement for milk production (MJ NE per year) will be the same regardless of whether the milk yield per year is expressed as an average for the herd or as individual daily milk yield.

Dairy cows: The following hierarchy is used to identify the milk yield of dairy cows (see Appendix 4, Energy requirement – Cows):

i) Measured milk yield (kg milk or kg ECM) per cow per day.
ii) Measured milk yield (kg milk or kg ECM) per cow per year,
iii) Milk (kg ECM) delivered to dairies. Corrections are made to consider on-farm consumption of milk (for calves, etc.).

If the milk yield is expressed as kg milk, then kg ECM is estimated based on the fat and protein content of the milk (measured or default values) (Appendix 4, Equation 4. 6). The milk yield reported for dairy cows excludes milk suckled by calves. Hence, NEL_{milk} is somewhat underestimated if the calves suckle extensively.

Beef cows: The milk yield of beef cows is not measured by farmers. The milk yield is assumed to be 2,000 kg per lactation for any beef cow (see Appendix 4, Energy requirement – Cows). This is seen as an acceptable generalisation; NEL_milk contributes to a minor share of NEL.

The energy requirement of cows is also affected by mobilisation and deposition. Mobilisation refers to the loss of body tissue when the cow is fed under energy requirements (negative energy balance). Deposition refers to the gain in body tissue when the cow is fed over energy requirements (positive energy balance). Typically, the energy balance is negative in early lactation and should be positive for a short period in mid lactation.

Mobilisation and deposition are not accounted for in the Agrosfär model since the carbon footprint should represent an annual average. On an annual basis, the energy supply from mobilisation in early lactation is assumed to be balanced by the deposition in mid lactation (Åkerlind, pers comm. 2021).

5.3.2 Growing cattle

5.3.2.1 Weight and Weight gain, kg

Data on current weight (kg live weight) and weight gain (kg live weight per day) is needed to calculate energy requirements. Typically, the animals are rarely weighted, and current weight and weight gain must be estimated based on (expected) weights on other dates. The following data is required:

1. Weight at birth: Default values from Norfor (Norfor, 2022). Default value is dependent on breed and sex (heifer, bull). This is seen as an appropriate assumption since there are minor differences (±7 kg) between breeds.
2. Weight as mature:
    - Heifers: The same assumptions as for cows, see above.
    - Bulls and steers: Default values from Norfor (Norfor, 2022). Default value is dependent on breed and sex (bulls, steer).
3. Weight (kg live weight) and age at least at one intermediate date, for example, at the end of the rearing period, when the animal is sold, or from weighing carried out during the rearing period:
    - Heifers: Weight and age at first calving. The weight is assumed to equal the mature body weight of cows of the same breed minus 100 kg. These assumptions are made to correlate the weight and weight gain of heifers with the weight of cows.
    - Bulls and steers: The following hierarchy is applied per individual:
        1. Data from weighing carried out during the rearing period.
        2. Slaughter data for the individual (age at slaughter and carcass weight). 1 kg carcass weight is assumed to equal 2 kg live weight.
        3. Average (for the farm) slaughter weight and age at slaughter for the category (bull/steer) and breed raised at the farm. 1 kg carcass weight is assumed to equal 2 kg live weight.
        4. Estimated based on default age at slaughter and body weight of mature males (breed-specific).

Current weight and weight gain is estimated in the same way as in Norfor (Volden, 2011), see Appendix 4 (Weight and weight gain – Growing cattle), Equation 4. 8-Equation 4. 11.

5.3.2.2 Energy requirement, NEG

The same equations are used to estimate the energy requirement of both dairy breeds and beef breeds, and for heifers, bulls and steers.

The net energy requirement, NEG (MJ NE per growing cattle and day), for growing cattle is estimated per head and day as (see Appendix 4, Energy requirement – Growing cattle):

$$NEG = NEG_{maint} + NEL_{gain} + NEL_{gest}$$

Where:

NEG_{maint} = Energy requirement for maintenance, MJ NE per growing cattle and day. NEG_{maint} is calculated as a function of the current body weight, activity, sex and breed (see Appendix 4, Equation 4. 13).

NEL_gain = Energy requirement for weight gain, MJ NE per growing cattle and day. NEL_gain is based on several sub-equations that estimate daily protein retention in the animal (g protein/day), daily fat retention (g/day), the efficiency of ME for maintenance and growth, and the utilisation coefficient of ME to NE for growth (see Appendix 4, Equation 4. 14 to Equation 4. 26).

NEL_gest = Energy requirement for pregnancy, MJ NE per heifer and day. This is the same as for cows (see Appendix 4, Equation 4. 3).

5.4 Feed characteristics

A nutrient profile of feeds is required to estimate feed intake (dry matter intake, DMI) and emissions from enteric fermentation and manure management. Data can be derived from feed analyses and databases, for example, feedstuff tables from Norfor or SLU[2]. However, the datasets may not be complete or contain all parameters required for the Agrosfär model. Many farmers analyse the nutrient content, for example, the energy and protein content, of crops grown on the farm, but other parameters that are required in the Agrosfär model may not be included in the analyses or be known by the farmer.

In addition, there are various methods to analyse the feed and the results from different methods may not be comparable. The energy content of feeds is expressed as net energy in Norfor's feedstuff table, whereas the energy content is expressed as metabolizable energy in SLU's feedstuff table.

Hence, two pathways have been described to characterise the feeds and to estimate DMI. The first and preferred pathway is called the **Norfor method**, which presumes that the net energy content of all feeds is known. The Norfor method has been implemented in the Agrosfär model. The second pathway is called the **IPCC method**. The IPCC method may be used if net energy content of the feed is unknown. The IPCC method requires that the digestibility (DE) of the feed is known, this can be found in some feed analyses and SLU's feedstuff table. So far, the IPCC method has not been implemented in the Agorsfär model.

In the current version of Agrosfär, the farmer chooses feeds from predefined lists of common concentrates and forage. The default net energy content, nutrient content, digestibility, carbon footprint, etc. is given for each feed. The farmer can manually alter the net energy content and protein content of some feeds, but is unable to add other feed parameters or new feeds to the table. There has been no need to implement the IPCC method since the list contains the net energy content of every feed available in the Agrosfär model. However, the IPCC method may be implemented in the future, for

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[2] https://www.slu.se/institutioner/husdjurens-utfodring-vard/Verktyg/

example, if further development of the Agrosfär model allows for farmers to add new feeds, or other data sources are integrated, that won't provide the net energy content of feeds.

5.4.1 Feed characteristics

The following parameters are needed per feed to estimate DMI according to the **Norfor** method:

- Dry matter content, DM [%]
- Particle size, PS [mm], or type of feed (concentrate or forage)
- Ash content or Organic matter content, OM [g/kg DM]
- Apparent total digestibility of organic matter OMD. OMD can be expressed as OMD, OMD20* and/or OMD8* [% of OM]
- Crude protein (CP), or Ammonia or urea corrected crude protein (cPcorr), and Ammonia and urea content (NH_3N) [g/kg DM]
- Crude fat (cFat) and fatty acids (FA) [g/kg DM]
- Net energy, NEL_{20}* and/or NEL_8* [MJ NE/kg DM]

* ”20” and ”8” represents the feed value at 20 kg DMI and 8 kg DMI, respectively. See section **Fel! Hittar inte referenskälla.**.

5.4.2 Definition of feed categories

The Agrosfär model needs to identify what category of feed each feedstuff belongs to. “Type of feed” is needed in the calculation of methane from enteric fermentation and can be used to set default values on nutrient content of feeds.

All feedstuffs are categorised into one of two main categories: i) Forage and ii) Concentrates. Norfor distinguish between forage and concentrate based on particle size, PS (mm). Feedstuffs with particle lengths >6 mm are defined as forage, feedstuffs with particle length ≤ 6 mm as concentrate (Volden, 2011).

Concentrates include a wide range of feedstuffs. In the current Agrosfär model, concentrates are further divided into the following subcategories:

a) Compound feeds and protein supplement.
b) Feed ingredients: cereal grains, peas, soy, by-products, etc.
c) Milk replacer: Fed only to calves.
d) Minerals: minerals, vitamins. No or very low content of organic matter.

Forage includes ley crops (grass, clover-grass, etc.), maize crops aimed for silage, and straw. In the Agrosfär model, forage is further divided into the following subcategories:

a) Harvested forage: Feed that is harvested and thereafter fed to animals (e.g., silage, hay and straw).
b) Pasture intake: Grazed directly by the animals.

In the current version of the Agrosfär model, the farmer has to provide information about the feeds used during the year and feed rations. The farmer has to choose between feeds from a database and is unable to add new feeds to the database:

- *Compound feeds and protein supplements*: The database contains default compound feeds and protein supplements aimed at dairy cows and growing cattle, respectively. The farmer must provide the average net energy content and protein content (MJ and g protein per kg DM) of the feedstuffs used, and the amount supplied to each animal subcategory (kg per animal subcategory and year). All compound feeds and protein supplements are assumed to be bought and brought to the farm.
- *Feed ingredients*: The database contains a set of common feed ingredients, for example oats, barley, wheat, soybean meal, rapeseed meal, distiller" grains, beet pulp and urea. For each feed ingredient used at the farm, the farmer must provide the amount supplied to each animal subcategory (kg per animal subcategory and year) and the amount bought. Default energy and protein content is given in the database.

  Milk replacers: The farmer indicates the amount of milk replacers bought and given to calves.
- *Forage:* The database contains a set of common forages, for example grass and clover silage (1st, 2nd, 3rd and 4th cut), maize silage, whole crop silage (e.g., oats and peas) and straw. It is assumed that the type of forage given to each animal subcategory is known, but the net consumption (kg DM) is unknown. Hence, the farmer has to indicate the proportion of each forage supplied to each animal subcategory (e.g., 70% grass and clover silage, 1st cut and 30% maize silage). In addition, the farmer must indicate the amount of forage bought to the farm (kg per year).

  The farmer must indicate the nutrient content of silage, either as g protein and MJ NE per kg DM or by indicating if the silage has high, medium or low digestibility.

In the current version of Agrosfär, the nutrient content and digestibility of pasture intake is assumed to equal harvested forage. The Agrosfär model estimates the amount of pasture consumed based on energy requirements during the grazing period.

Minerals, vitamins, etc. are not included in the current version of the Agrosfär model. They are fed in very small amounts and contain no or little organic matter. Hence, it is assumed that minerals can be excluded with no effect on emission calculations (emissions from enteric fermentation and manure management) and the total carbon footprint of feeds.

5.5 Estimation of dry matter intake – the Norfor method

Given that the DMI of forage is unknown, the daily feed intake (dry matter intake, DMI, kg DM per day) is estimated based on net energy requirements.

DMI can be estimated in two ways, depending on the feed evaluation system applied.

- Norfor method: Based on net energy. The net energy content of feeds must be provided (NEL_{20} and/or NEL_8). This is the suggested option and is implemented in the current version of Agrosfär.
- IPCC method: Energy requirements are estimated as net energy, but the feed digestibility is used to estimate feed intake. The digestibility of the feed must be provided. The IPCC method is not yet implemented in the Agrosfär model as the feed database in Agrosfär contains all required information needed to apply the Norfor method and the farmer can't add new feedstuffs to the database.

The energy balance, that is the energy supplied from the feed ration divided by the total energy requirement, is assumed to be 100% on average per animal and year. Ideally, the energy balance should be 100%. However, the animals can consume more (or less) feed, which results in a higher (or lower) energy balance. In the long run, the animals will gain more fat if the energy balance is higher than 100%.

Note that the amount of feed given to the animals can exceed the amount of feed consumed by the animals. Some feed can be left uneaten (see section 5.9.3). Uneaten feed is not included in the estimations of emissions from enteric fermentation and manure management. The fate of uneaten feed may be included later.

5.5.1 Estimation of energy content of feed

The net energy supply from feeds (MJ NE per kg DM) depends on several parameters, such as dry matter intake (DMI). High feed intake implies the faster passage of the feed through the rumen and intestines, and lower utilisation efficiency of the energy content of the feed. Hence, a lactating dairy cow with high DMI will utilise less of the energy content of the feed than a dry cow that eats less.

The Norfor system accounts for this aspect and estimates the net energy value for a feed ration based on, for instance, DMI. These estimations are refined and are too detailed to be implemented in the Agrosfär model. However, standard feed values on the net energy content of feeds can be found in feed analyses and the Norfor feed table. These standard feed values are given for two levels of DMI, 20 kg DMI (NEL_{20}) and 8 kg DMI (NEL_8). The NEL_8 value of a feed is higher than the NEL_{20} value.

It is assumed that the NEL_{20} and NEL_8 of feeds can be used as an approximation for the net energy supply from the feed ration. The Norfor feed table contains NEL_{20} and/or NEL_8 for many feeds, whereas the net energy content is usually expressed as NEL_{20} in feed analyses and data from feed suppliers. In the current version of Agrosfär, NEL_{20} is assumed to be known for all feedstuffs. The farmer must supply NEL_{20} for some feedstuffs (e.g., compound feed and protein supplements), and there are default NEL_{20} for all feedstuffs in the database.

In addition, the gross energy content of feeds is needed to estimate methane emissions from the enteric fermentation of growing cattle. The gross energy content of feeds is calculated based on their fat, protein and carbohydrate content (see Appendix 4, Equation 4. 27).

5.5.2 Dry matter intake

It is important to know the amount of feed consumed by the animals (kg DM per feed and per day). The total feed intake (DMI, kg DM per animal and day) must be known as it is used to calculate methane emissions from enteric fermentation, both from cows and growing cattle. We also need data on average feed characteristics (fatty acids, NDF and ash) and the proportion of concentrates in the feed ration for growing cattle.

The feed ration is not constant or the same for all animals. The feed ration varies during the year; there are, for example, differences between the grazing period (up to 100% of energy supply from pasture) and the winter/stable period. Lactating cows are fed much more concentrates than dry cows. The feed ration varies as the growing cattle gets older.

The data quality and availability vary regarding the amount of feed fed to the animals. The amount and feed values of concentrates is generally recorded, and the farmer knows if the concentrates are given to cows and/or growing cattle. On the other hand, the quality and yield (kg DM per hectare) of pasture is not known in as much detail.

The following assumptions are made regarding **concentrates** (see Appendix 4: Equation 4. 29 to Equation 4. 32 and Equation 4. 38 to Equation 4. 41):

- The amount of every concentrate fed to cattle is known(i.e., kg concentrate per year fed to dairy cows, beef cows and growing cattle, respectively).
- Dairy cows:
    - Concentrates allocated to dairy cows are assumed to be given to lactating cows. Hence, dry cows do not eat any concentrates.
    - Lactating cows are fed concentrates all year around.
    - The concentrates are distributed between lactating cows in proportion to their energy requirement.
- Growing cattle and beef cows:
    - Growing cattle and beef cows are fed concentrates during the stable period.
    - The concentrates are distributed between growing cattle in proportion to their energy requirement.
    - The concentrates are distributed between beef cows in proportion to their energy requirement.

The following assumptions are made regarding **grazing and pasture intake** (see Appendix 4: Equation 4. 33, Equation 4. 34, Equation 4. 42 and Equation 4. 43):

- The grazing period is recorded separately for the lactating dairy cow, dry cow, beef cow, bull, and heifer/steer categories.
- For the current version of Agrosfär, the feed value of pasture is assumed to equal the feed value of harvested forage fed to each animal subcategory.
- The farmer provides data on the grazing period, such as length of the grazing period (start and end date, every animal subcategory).
- Dairy cows:
    - All dairy cows are assumed to graze.
    - The farmer indicates the duration (0-24 hours per day) for lactating and dry cows separately.
    - The energy supply (MJ) from pasture intake is assumed to be proportional to the duration, these are the same the assumptions made in the advisory tool VERA. If the cows graze 6 hours per day, then pasture intake constitutes 6/24 = 25% of their energy supply.
- Beef cows:
    - All beef cows are allowed to graze.
    - The animals are assumed to graze 24 h/day.
    - Pasture intake constitutes 100% of the DMI during the grazing period.
- Bulls, heifers, and steers:
    - As a default, all cattle older than 6 months are assumed to graze during the grazing period, as stipulated by law. However, bulls are exempt from these requirements. Hence, the farmer has to provide the number of grazing periods for growing bulls (0, 1, 2 or 3 seasons)
    - Dairy breeds: Cattle younger than 6 months do not graze. If they turn 6 months old during the grazing season, they start grazing from the day they turn 6 months (e.g., the grazing period for heifers is May 1 to September 1. A heifer born February 1 will be grazing August 1 to September 1).
    - Beef breeds: Calves of beef breeds are assumed to follow their mother pre-weaning. Hence, the grazing period for cattle younger than 6 months is assumed to be the same as for beef cows (e.g., the grazing period for beef cows is May 1 to September 1. A calve born February 1 will be grazing from May 1, although it is younger than 6 months).
    - The animals are assumed to graze 24 h/day.
    - Pasture intake constitutes 100% of the DMI during the grazing period.

The following assumptions are made regarding **forage** (see Appendix 4; Equation 4. 35 to Equation 4. 37 and Equation 4. 44 to Equation 4. 46):

- The farmer can roughly estimate the amount of forage fed to cattle, and roughly distribute the amount between dairy cows, beef cows and growing cattle.

- The amount consumed is estimated as the difference between the calculated energy requirement and energy supplied from concentrates and pasture intake (e.g., if the energy requirement of a lactating dairy cow is 150 MJ NEL per day and the energy supplied from concentrates correspond to 55 % of her energy requirements, then harvested forage = 150 MJ NEL*(1–55 %) = 67.5 MJ NEL. If the energy content of harvested forage is 6.1 MJ NEL_{20}/kg DM → 67.5/6.1 = 11.1 kg DM harvested forage per day).

The total DMI (Appendix 4, Equation 4. 47) and gross energy intake, GEI (Equation 4. 48) is then summarised per head and day. The average nutrient content of the feed ration is estimated as well (Equation 4. 49).

Comments regarding **young calves**: Young calves (pre-weaning) do not emit (or emit small amounts of) methane from the rumen (Gavrilova et al., 2019). The IPCC guideline suggests that the methane conversion rate is zero for juveniles consuming only milk, which implies zero methane emissions from the enteric fermentation of juveniles. In the Swedish NIR, the pre-weaning period is assumed to be two months for calves of dairy breeds and three months for calves of beef breeds.

These assumptions are implemented in the Agrosfär model by excluding the energy requirements of calves pre-weaning. Hence, we don't need to consider and distribute energy supply from milk replacers intended for calves pre-weaning. However, this simplification implies that N and VS excreted pre-weaning is excluded and that the excretion rates of growing cattle is underestimated. The excretion rates are determined from the feed intake, the feed intake is determined from the energy requirement, and the energy requirement of young calves is excluded in NEG. However, N and VS excreted by calves is assumed to be negligible compared to the excretion rates and number of older animals.

The weaning age is assumed to be 2 months for calves of dairy breeds and 3 months for calves of beef breeds (Naturvårdsverket, 2021a). These weaning ages are applied for organic and conventional production systems alike. However, dairy calves in organic production are weaned at a greater age. This is assumed to have a negligible impact on the results since it a short difference in time and the energy requirements of small calves are low compared to older animals.

5.6 Enteric fermentation

Methane from enteric fermentation is estimated in the same way as in the Swedish NIR (Bertilsson, 2016; Naturvårdsverket, 2021a) (see Appendix 4, Equation 4. 50). There are separate equations for cows and growing cattle. The emissions are estimated per head and day.

Methane from **cows** is estimated based on dry matter intake (DMI) and the concentration of fatty acids in the feed ration (see Appendix 4, Equation 4. 51). The higher the DMI, the higher the methane emissions. The higher the fatty acid content, the lower the methane emissions. The same equation is used for dairy and beef cows.

Methane from growing cattle is estimated based on the feed intake and proportion of concentrates in the feed ration (% of DM) (see Appendix 4, Equation 4. 52 and Equation 4. 53). The feed intake is expressed as gross energy, MJ GE per head and day. The higher the gross energy intake, the higher the methane emissions. The more concentrates in the feed ration, the lower the methane emissions.

Note that the energy requirements and methane emissions from calves pre-weaning are excluded. The pre-weaning period is assumed to be two months for calves of dairy breeds and three months for calves of beef breeds.

5.7 Manure management

This section covers emissions from the stable (NH_3), storage of manure (NH_3, N_2O and CH_4) and manure deposited on pasture (NH_3, N_2O and CH_4) (see Figure 3). Emissions from manure management depend on housing and manure management systems, and on the amount of N and VS (volatile solids) excreted by the animals. Major housing and manure management systems are included. However, treatment of manure, for example anaerobic digestion, separation of slurry or acidification of slurry, is not yet included.

In the Agrosfär model, emissions of CH_4 and N_2O from manure dropped outdoors on pasture and range are included in manure management. This is a different to the IPCC guideline, in which CH_4 is reported as emissions from Manure Management, whereas N_2O is reported as soil emissions. However, the crop production sub model in the Agrosfär model does not cover soil N_2O emissions induced by manure deposited on pasture by grazing animals.

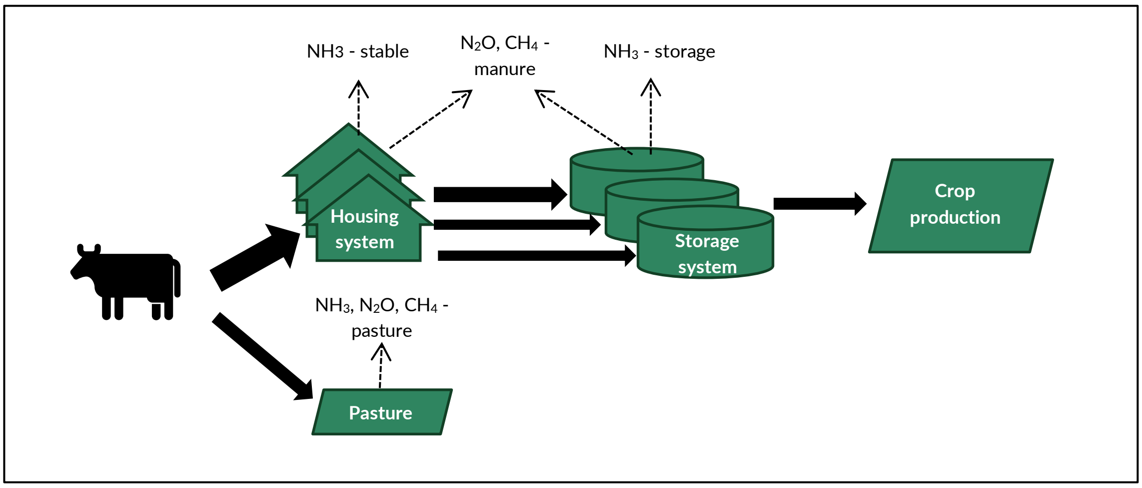

Figure 3. Illustration of flows of manure (black arrows) between compartments (yellow areas), and emissions from the manure management system (dotted arrows). Emissions from the spreading of manure is described in the section on crop production.

5.7.1 Housing systems and manure storage systems

Emission rates depend on the housing system and the manure storage system(s) on the farm, as well as the distribution of manure between systems.

The following data is provided by the farmer:

- For each animal category: Housing system(s) and the number of heads per housing system if there are multiple systems. The animal categories are lactating dairy cows, dry dairy cows, beef cows, heifers, bulls, and steers.
- Coverage of manure storage: The share (%) of slurry and urine stored with and without cover (crust or coverage).

Comments on housing systems:

The aggregation and disaggregation of animal categories aims to facilitate data collection. These categories and structures (heads per manure management system) should be known by the farmer and are similar to the categories applied in VERA. If desired, the animal categories may be disaggregated further in the future, for example, to separate replacement heifers of dairy breeds and heifers of crossbreeds aimed for meat production, or to separate calves pre-weaning from other growing cattle.

During the grazing period, VS and N excreted is allocated to pasture proportionally to the duration of grazing (h/day). Some cattle can go outdoors during the stable period. However, manure dropped outdoors during the stable period is not counted.

Some housing systems generate two types of manure, such as systems where manure is separated in the stable into a solid fraction (solid manure) and a liquid fraction (urine), and the fractions are stored separately. In this case, N and VS excreted indoors is automatically distributed between the solid and liquid fraction dependent on the fate of faeces and urine deposited by the animals. It is assumed that 100% of the faeces and 25% of the urine ends up in the solid fraction, and 75% of the urine in the liquid fraction. It is assumed that 100% of VS is excreted as faeces, and that 50% of N is excreted as faeces and 50% as urine. This is the same distribution as the general assumption in the IPCC guidelines (chapter 10.5.2) (Gavrilova et al., 2019).

The N and VS excreted indoors is allocated between housing systems proportional to the fraction of each animal category assigned to the system. Hence, the proportion between different types of manure (slurry, solid, deep bedding, and urine) produced per animal category will be the same, although the number of animals may vary over the year or may differ from the information given by the farmer. In the case of a farmer saying that there was 40 heifers on deep bedding and 60 heifers loose on slurry, then 40% of N and VS excreted would be handled as deep bedding and 60% as slurry, regardless of the number of heifers on the farm and the age of the heifers.

This approach may skew the distribution between manure systems, for instance, if young calves are housed on deep bedding but the manure from older heifers is handled as slurry. However, it is assumed that the proportional distribution of manure is suitable and sufficient for the Agrosfär model and reduces the risk of errors in data collection.

Comments on manure storage systems:

The manure can be handled and stored as slurry, urine, deep bedding, or as solid manure. Emission rates differ between the types of manure. The following assumptions are made about each type of manure:

- **Slurry**: Emission rates depend on the coverage of the storage. Three alternatives are given: Natural crust, Other cover (e.g. lid), or No cover.
- **Urin**e: Emission rates depends on the coverage of the storage and whether urine is stored separately or with slurry. Three alternatives are given: Stored with slurry, With cover (e.g. lid), or Without cover.
- **Deep bedding and solid manur**e: No differences in emission rates between storage schemes.

5.7.2 Methane emissions

Methane from manure management is estimated as a function of VS excretion rates, the maximum methane-producing capacity of the manure (B_o), and a Methane Conversion Factor (MCF) (see Appendix 4, Equation 4. 54 to Equation 4. 55). The method is similar to the Tier 2 approach in the IPCC guidelines (Gavrilova et al., 2019).

The **VS excretion rate** is calculated as a function of DMI, ash content in feeds, and the total apparently digested organic matter (td_OM). DMI is estimated in the Agrosfär model, and the ash content is generally known. td_OM is not known as frequently but can be found for a range of feeds in the Norfor table (td_OM20 or td_OM8) or can be estimated as a function of the apparent total digestibility of organic matter.

The maximum methane-producing capacity of the manure, **B_o,** is expressed as default values. The B_o values comes from the IPCC guidelines and refers to cattle in Western Europe (Gavrilova et al., 2019). B_o for manure from dairy cows is higher (0.24 m^3 CH_4 per kg VS) than for manure from other cattle (0.18 m^3 CH_4 per kg VS). Dairy cows have high feed intake, which implies lower utilisation efficiency of the energy content of the feeds and that more easily degraded organic compounds remain in the manure.

More specific B_o values are preferred but are not yet available.

MCF describes the amount of methane produced in relation to B_o and is expressed as % of B_o. The MCF depends on the manure management system. Methane is produced under anaerobic conditions (no oxygen available), and the methane production rate depends on the temperature. The following national adopted methane conversion factors are applied (Naturvårdsverket, 2021a):

- Slurry and urine: 3.5%. Low MCF, although the environment in slurry and urine is anaerobic. Frequent removal of manure from the stables and low ambient temperature contributes to low methane emissions under Swedish conditions. This MCF is much lower than the default MCF for slurry in the IPCC guidelines. The default MCF is 9% and 14% for slurry stored for 4 and 6 months, respectively, in boreal climate (Gavrilova et al., 2019).
- Deep bedding: 17%. Higher MCF due to the composting process that produces heat and consumes oxygen, which may imply partial anaerobic conditions.
- Solid manure: 2%. Low MCF due to aerobic conditions.
- Manure dropped on pasture: 1%. Low MCF due to aerobic conditions.

5.7.3 Direct nitrous oxide emissions

Direct N_2O emissions, dN_2O, from the storage of manure is estimated as a function of N excretion rate and emission factors (see Appendix 4, Equation 4. 56 to Equation 4. 62). The calculations are based on the IPCC method. The Norfor method can be used to estimate N excretion rate, but there is no information on how N_2O emissions are estimated in the Norfor system.

Direct N_2O emissions are estimated as a function of an emission factor and the amount of N excreted by the animals. The amount of N should reflect the amount of N prior to losses of ammonia.

The **emission factor** describes the share of N excreted that is converted and emitted as N_2O (kg N_2O-N per kg N excreted). The emission factor depends on the manure management system. The following national adopted emission factors are applied (Naturvårdsverket, 2021a):

- Slurry, urine and solid manure: 0.005 kg N_2O-N per kg N
- Deep bedding: 0.01 kg N_2O-N per kg N
- Manure dropped on pasture: 0.02 kg N_2O-N per kg N

The total amount of **N excreted** in urine and faeces is estimated based on the Norfor method (Volden, 2011). N excreted is the difference between the intake of N and the retention of N in body tissue (foetus and weight gain) and milk (protein content in milk). Intake of N is estimated based on DMI and the protein content of the feed ration.

There are equations in Volden (2011) on how to separately report N excreted in faeces and N excreted in urine. However, there are many sub-equations and parameters needed on the digestion of protein and organic matter. It is concluded that the great effort needed to acquire this separate data is not proportional to the gain of reporting N content separately in the Agrosfär model. Most cattle manure is handled as slurry, and less and less as solid manure or urine. The N_2O emission factors for Solid manure and Urine are similar, so the exact fate of N excreted is not crucial. In addition, solid manure is "contaminated" by urine and vice versa.

5.7.4 Indirect nitrous oxide emissions

Indirect N_2O emissions, iN_2O, from stable and storage of manure is estimated as a function of N excretion rate, N in bedding materials and emission factors that describe ammonia emissions (kg NH_3-N per kg N in manure, including bedding materials) and the conversion of NH_3 to N_2O (see Appendix 4, Equation 4. 63 to Equation 4. 68). The calculations are based on the IPCC method but supplemented with national emission factors for ammonia.

The **emission factors for ammonia** come from supporting material to the Swedish advisory tool VERA. These emission factors comprise ammonia emissions from stable and storage of manure, respectively, including N in bedding materials. Hence, N in bedding materials is added when ammonia emissions are estimated. In addition, the emission factor for the storage of manure is expressed as a fraction of N remaining in the manure post NH_3 emissions that occurred previously in the stable.

The amount of **bedding materials** is estimated as default values (kg bedding material per head and day) per housing system and animal category (dairy cows, beef cows, heifers, bulls, steers). Default values comes from VERA. The bedding material is assumed to be straw, and the N content of straw is 0.007 kg N per kg straw.

The **emission factor for indirect N_2O** comes from the IPCC guidelines. The default aggregated value is applied, which is 0.01 kg N_2O-N per kg NH_3-N emitted (Gavrilova et al., 2019).

According to the IPCC guidelines, the estimation of iN_2O should include N leaching from manure management, through runoff and leaching from, for example, the storage of solid manure and where animals are grazing in pastures. However, it is assumed that N leaching from manure management is insignificant and is not included in the Agrosfär model.

5.8 Dead cattle

Cattle which die on the farm or are slaughtered prematurely, and where the meat cannot be sold are included during the period they are alive. Thus, feed consumption, enteric fermentation and manure production are calculated up to the death of the animal. The carcass weight is not included in the output from the production, and the burden of the dead animal's life is carried by the total output from animal production. The waste handling of the carcass was not included in the current version of Agrosfär.

5.9 Feed waste and losses

5.9.1 Storage losses of silage

Losses of silage during storage are losses caused by the silage process and microbial digestion of the matter. These losses are about 1% of DM for round bale silage, with losses being greater, about 20% of DM, for bunker silos, stack silage and tower silos (Abrahamsson, 2012; Spörndly and Nylund, 2017). These losses are not accounted for in the current version of Agrosfär.

5.9.2 Unusable feed

Unusable feed is feed which has become unfit for feeding before being given to animals (e.g., due to mold). The magnitude of these losses depends partly on the storage method. For round bale silage, losses are usually low, up to 8%, as they do not need to stay open for long due to their small size (Bannbers et al., 2021; Spörndly and Nylund, 2017). For different types of silo, losses appear to be higher, although there are large differences between different studies and between different farms within the same study, ranging from 0 to 35% (Bannbers et al., 2021; Spörndly and Nylund, 2017). For concentrate feed, we have found no literature covering losses. Losses from feed being unusable are not included for the current version of Agrosfär. In coming versions, it will be included as a higher feed input needed for the production; however, waste management of this feed will not be included in the model.

5.9.3 Uneaten feed

Uneaten feed is feed which was given to livestock but left uneaten. Again, we have found no data covering uneaten concentrates, but since this kind of feed is particularly tasty for the animals, we have assumed a low loss rate, 0.5%, for all feeding arrangements. For forage fed indoors, we have assumed 4% losses, based on information from Hessle (2021), Bannbers (2021), Lindström and Gren (2009) and DairyNZ (2017).

5.10 Carbon footprint of inputs

The current version of Agrosfär includes the carbon footprint (CF) of feedstuffs, but no other inputs. Default CF of feedstuffs is given in a database (kg CO_2-eq per kg or per kg DM). These footprints are primarily derived from the dataset on default carbon footprints of feed ingredients accompanying the Swedish framework for carbon footprint of feeds (Foder och Spannmål, 2022). This framework is based on PEFCR on feed for food producing animals and has been adapted to Swedish conditions. Carbon footprints of compound feeds are derived from feed companies, who calculate the carbon footprints based on the framework from Foder och spannmål. The carbon footprint of feedstuff that are not included in the dataset from Foder och spannmål are derived from Flysjö et al. (2008), Landquist et al. (2020), Mogensen et al. (2018) and Woodhouse (2019).

When the results of the Agrosfär model is presented on a product level (kg CO2-eq per kg ECM and kg live weight, respectively), the same CF is applied for purchased feedstuffs as feedstuffs grown on the farm. In the future, the CF of feedstuffs grown on the farm will be calculated and integrated with the crop production sub-model.

6 Total energy use on the farm

The total climate impact from energy use on the farm is calculated from measured annual electricity use, fuel consumption and, if relevant, the use of district heating/cooling (Appendix 5, Equation 5. 1). Data for total energy use per fuel type and per usage area is given by the Agrosfär user.

Emission factors for fuel, electricity and district heating are from Energimyndigheten and Energiföretagen.

7 Future improvements

In the following section, potential improvements to the Agrosfär tool are described. Some improvements are dependent on the development of calculation procedures or the establishment of scientifically accepted methods; these improvements may be implemented in the long-term. Other improvements can be directly implemented in the tool in a second version.

7.1 System boundaries and system scale

7.1.1 Capital goods, infrastructure, and machinery

Capital goods, infrastructure and machinery has not been included in Agrosfär so far. The requirement for inclusion according to guidelines varies. ISO and GHG Protocols do not require the inclusion of capital goods. According to PEFCR, capital goods, including infrastructure, can be excluded if their contribution to GHG emissions is less than 1% of total GHG emissions. According to PEFCR, dairy capital goods at the dairy unit can be excluded as they generally contribute to more than 1% of the total GHG emissions. GFLI includes the depreciation of capital goods and machinery needed for practicing cultivation and storage. In future versions of the Agrosfär tool, capital goods can be included, possibly by using default emission factors. How and which capital goods to include needs further discussion.

7.1.2 Connection between animal and crop model

The animal and crop model will be more closely interlinked in future versions of the tool. Manure produced in the animal sub model can be transferred to the crop production sub model. However, this requires solving the question regarding addition of water and other substances to the manure as the manure production is estimated as kg N per year, not ton manure per year, and the application rates are given as ton per hectare. In addition, the fate of the manure produced has to be identified, whether it is used in crop production on the farm and/or is exported.

From the crop model, actual information on amount of feed produced could be matched with the animal model; however, this requires the model to be able to account for feed stock changes between years and the tracking of information about amount of feed being sold from the farm and feed being fed to on farm animals.

Energy is used on the farm both in crop and animal production. In a future version of the tool, information on energy use – electricity and fuel – should be allocated either to crop or animal production. See more in section 7.6.

7.1.3 Uncertainty ranges

In the current version of Agrosfär, uncertainty ranges are not included, such as for emission factors used for direct N_2O emissions. Before including uncertainty ranges, it is important to consider what value the inclusion of uncertainty ranges will bring to the user and in that case, what type of uncertainty is most important to communicate to the user of the tool.

7.2 Nitrous oxide emissions

N_2O emissions make up a great part of the crop production GHG emissions; the method for calculating N_2O emissions is therefore of great importance. Alongside this, the N_2O emissions are one of the most uncertain parts of agricultural climate estimations. Despite these uncertainties, there are a few suggested improvements for the calculations:

7.2.1 Direct N_2O from soil

Currently the aggregated method for calculating N_2O emissions from IPCC 2019 is used. In the future, it might be an option to use disaggregated emission factors, specified for climate type (dry/wet) and fertiliser type. However, the disaggregated emission factors provided in IPCC 2019 are designed from global averages, and there are major uncertainties regarding whether these would provide more accuracy to the model than using the aggregated values.

In the current model, it is not taken into consideration that more N_2O is released when soil-C is higher. This could be included in a second version of the model providing that there is enough scientific evidence and available emission factors.

7.2.2 N_2O from crop residues

The calculation of nitrogen turnover from crop residues builds on a generic value for the ratio between crop yield to crop residues. The yield to crop residue ratio builds on IPCC 2019 values. For some crops, the IPCC ratios are not representative for Swedish production. Using values from the Swedish NIR report was discussed, which are adopted to Swedish conditions and the list of crops is more extensive than IPCC, but the NIR values overestimate N_2O emissions for potatoes, sugar beets and tubers; It was therefore decided to use IPCC values.

The ratio between crop yield to crop residue can be misleading for some crops, such as ley cultivated for ley-seed production, where a much smaller yield is harvested than for ley harvested for silage production. In Agrosfär, this is solved by adding a “thought” yield level. It needs to be investigated if this provides a fair representation.

The method for the calculation of crop residues is unclear in IPCC for crops where the harvested part is below ground, such as sugar beet or potatoes. It is not clear whether the roots and tubers should be treated as below ground biomass or above ground biomass in the calculations, as they are removed from the field and should not contribute to N_2O emissions from crop residue N turnover in soil. This needs further investigation.

In the current Agrosfär tool, values for “grain” are used when calculating N_2O emissions (above and below ground biomass, etc). There is an option of using more disaggregated values per crop, such as winter wheat, barley, etc (table 11.1A, Hergoualc’h et al. (2019)). It should be investigated how disaggregation would impact the results and whether it is applicable for Swedish production of grain.

Some crop residues have faster turnover than others (e.g., sugar beet tops vs straw) which could influence N_2O emissions. This is not included in the present model but could be a future improvement as science progresses.

7.2.3 Indirect N_2O emissions from soil

NH_3 emissions contribute to indirect N_2O emissions. Currently, the farmer needs to provide information in the Agrosfär model on the timings of manure spreading, which has an impact on NH_3 emissions. As Swedish regulations do not allow for manure to be spread during certain parts of the year for different regions, an alternative method could be to use the location of the farm as the basis for spreading time of manure. There are also emission factors available for indirect N_2O emissions (NH_3 emissions) disaggregated by climate zone and fertiliser type; this could be developed in a future version but requires a climate division of the Swedish municipalities.

7.2.4 Pasture emissions

Pasture emissions are only partially covered in the Agrosfär model. Indirect N_2O from N-leaching in pastures is not included. As these grasslands are usually nutrient poor, we can expect these emissions to be very low and are therefore not included in the model. However, for completeness, these should be added. Further, emissions from more carbon and nutrient rich semi-natural pastures should be included in a later version of the Agrosfär tool.

7.3 Emissions from organic soils

Currently, N_2O and CO_2 emissions from organic soils are included by using default emission factors, applied on all soils with an organic matter content >40%. This is according to PEFCR dairy. However, PEFCR feed requires that CO_2 emissions shall be calculated based on a model that relates the drainage levels to annual carbon oxidation. Also, FAO LEAP suggests that collecting data on groundwater levels and using emission factors relating to soils with different groundwater levels. When an appropriate model is available for such an inclusion, this can be included in the Agrosfär tool.

Emissions of CO_2 and N_2O from organic soil pastures are not included. Even though these types of soils are rare, a farm could have the bad luck of having many of these types of soils. However, emission factors have been prepared for pastures on organic soils and these can be included in later versions of the Agrosfär tool.

7.4 Animal production model

7.4.1 Dry matter intake, DMI

DMI of forage (silage, hay and other harvested crops) is estimated based on calculated energy requirement but could be developed so that the farmer would be able to submit the actual amount fed to the animals.

Another possible future improvement could be the development of a sub model to predict dry matter intake based on the IPCC method. The IPCC method would be useful when the net energy content of feeds (MJ NE) is unknown or if required to harmonize with LCA standards.

In some production systems, the dairy calves suckle for many weeks/months. Hence, the DMI of dairy cow is underestimated since the milk consumed directly by the calve is not included in the milk yield. A future improvement is to identify these production systems and to account for milk consumed directly by the calves.

7.4.2 Waste and losses

Standard figures for feed losses during and after storage but before feeding should be determined per storage method. Discharged feeds that end up in the manure will increase nutrient content and emissions from manure management, and this should be included. It should also be determined how to handle the possibility of excessive feeding.

Waste handling of animals dying on the farm should be included in coming versions of Agrosfär.

7.4.3 Growing cattle

Emissions associated with young calves are mostly excluded since they are assumed to be of minor importance. The current version of Agrosfär includes the carbon footprint of milk substitutes but excludes energy requirements and emissions from enteric fermentation and manure management of milk-fed calves. Future improvements:

- Include manure management systems and feeding regimes for calves in the Agrosfär user interface and the associated calculations of greenhouse gas emissions.
- Ensure that the energy requirements of calves pre-weaning and the nursing cows are not double counted.

The dry matter intake (DMI) of growing cattle is estimated based on energy requirements, but the protein supply may restrict the growth of growing cattle. The estimation of DMI could be improved by including the protein requirements of growing cattle.

7.4.4 Grazing and pasture intake

So far, the quality of pasture intake is assumed to equal the quality of harvested forage. However, pasture intake can have a lower energy content and lower digestibility than forage consumed during the housing period. The quality of pasture intake and forage will be separated in future versions of the Agrosfär model. In addition, cattle may be fed additional forage during the grazing season, which is not counted in the current version of Agrosfär but may be included later.

The demands on grazing and outdoor access are higher and more detailed in organic cattle production than in conventional production. There are requirements regarding pasture intake (% of DMI), duration of the grazing period, and access to the outdoors during the outdoor period (i.e., the time before and after the grazing period) in KRAV-certified production. These requirements could be accounted for in future version of Agrosfär.

7.4.5 Purchased cattle

The carbon footprint of cattle brought to the farm is not included yet but will be accounted for in future versions of Agrosfär. This includes the carbon footprint of cattle that are purchased (e.g., dairy bull calves that are bought and raised for meat production) and greenhouse gas emissions from the rearing of heifers outside the farm.

7.4.6 New version of IDF Guideline

In 2022, IDF published updated guidelines for the calculation of carbon footprint in the dairy sector (IDF N°520/2022: The IDF global Carbon Footprint standard for the dairy sector). A future improvement is to update the current model according to the new guidelines, for example, updating the allocation factor between milk and meat.

7.5 Manure

The content of N, P, K in manure can be refined. We know the amount of N excreted from animals and the amount of N in stored manure (slurry, solid manure, deep bedding and urine, respectively) expressed as kg N per year, but we don't know the concentration of N in the manure expressed as kg N per ton of manure since we don't know the amount of water added to the manure (water in urine and faeces and water used in the stable, rain, drainage) and, hence, the total amount of manure produced (ton manure per year). In addition, the P and K excretion rates could be included in Agrosfär. In crop production, "standard" values are used, not actual values from the animal production model.

7.6 Energy use and biogenic emissions

Total energy use is covered in the Agrosfär tool. The fuel used for field operations and energy used for crop drying is allocated to the specific crop. The remaining energy use is reported in the farm level calculations but is not yet attributed to crops or animal products in the product perspective calculations. In a future version of the tool, information on energy use – electricity and fuel – should be allocated either to crop or animal production.

Currently, drying of crops is estimated based on kg of water dried, using default values for energy required for the drying of 1 kg of water or if the farmer has actual figures, on energy used for drying. This method could possibly be refined in future versions.

Biogenic emissions, CO2 emissions from combustion of biomass, will be included in the coming versions of Agrosfär.

7.7 Land use change and land management

According to most LCA standards, land use change (LUC) and soil carbon changes due to land management should be included but reported separately. For purchased feed, this is included in the Agrosfär model by generic numbers provided by feed producers. This could be further developed by implementing established models for assessing direct LUC in the tool.

Accounting for soil carbon changes caused by land management is more difficult. Models for calculating soil carbon changes exist, such as Roth-C, ICBM, Odlingsperspektiv, IPCC, as well as results from long-term field trials, but guidelines for how to account for and include soil carbon changes in climate assessments is still under discussion as the time perspective and how to ensure permanency are complex issues.

The Greenhouse Gas Protocol is currently developing Land Sector and Removals Guidance (LSRG). LSRG explains how GHG emissions and removals from land management, land use change, biogenic products, and carbon dioxide removal technologies should be accounted for and reported. The ambition is that the guideline will be included in the coming versions of the Agrosfär tool.

7.8 Other land use

On a farm, there will be land used for other purposes than exclusively for food production, such as fallow land, flower, riparian buffers and hedgerows, which can be grown for biodiversity preservation purposes or for other environmental enhancement purposes. When calculating GHG emissions on an enterprise level, such land use should also be included if it is a part of the crop, dairy or beef enterprise but is not relevant when calculating climate impact on a product level.

If the farmer also grows forest, this is usually treated, both economically and physically, as a separate enterprise and is not included as a part of the total farm GHG assessment. It can, however, be calculated separately and will also require a separate model. However, trees can be planted in groves as a part of the crop/dairy or beef enterprise as an agroforestry measure, without the intention of being logged for, for example, pulp production. In this case, the trees can be considered as a part of the food production system and can be included in carbon sequestration calculations in biomass or soil if such a sub-model is included in the Agrosfär tool.

7.9 Straw

In the crop production model, removal of straw is included as it affects nitrous oxide emissions. However, straw is not treated as a product, and no allocation between grain and straw is made. In the animal production model, straw is included in the manure emission calculations (ammonia emissions) but is not treated as a product and has no upstream climate impact connected to it. This means that emissions from the gathering, bailing and transport of straw are not separated from crop production in the current version but are included in the overall diesel use. In a coming version, this should be separated and allocated to the livestock production in cases where the straw is used as bedding material. This would be in line with the FAO LEAP standard, which recommends that only the straw-specific steps of production are attached to the straw.

7.10 Other inputs

The Agrosfär model includes major inputs that contribute significantly to the total GHG emissions. Other inputs are generally of low importance for the total GHG emissions and have not been prioritised in the current version. Other inputs not currently considered, which should be considered in a coming version of the tool, are:

- Plastic for silage and straw
- Bedding material other than straw (e.g. peat)
- Refrigerants for cooling of milk

7.11 Waste handling

Handling of waste (manure not included), such as the share of waste recycled, does not usually contribute significantly to carbon footprints from agricultural products. In the current version of Agrosfär, handling of waste, including silage plastics, packaging of fertilisers and feed waste, is not included, but this is a possible area for improvements in later versions of the model.

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Appendix 1: Compliance with Greenhouse Gas Protocol

This section describes the compliance of the Agrosfär tool with the Greenhouse Gas Protocol Corporate Standard and Greenhouse Gas Protocol Agriculture Guidance (Scope 1 and 2) and the Corporate Value Chain (Scope 3) Accounting and Reporting standard. The Greenhouse Gas Protocol Agriculture Guidance largely summarizes and customizes the content from the Corporate Standard to the agricultural sector. The focus is to describe how the Agrosfär tool and reporting deviates from GHG Protocol requirements on accounting and reporting. The Greenhouse Gas Protocol differentiates between “shall” and “should” requirements. The term “shall” indicates what is required for a GHG inventory to be in conformance with the GHG Protocol Standard. The term “should” indicates a recommendation, but not a requirement. In the compliance check, the focus is on “shall” requirements, however several “should” requirements are included for the Agricultural Guidance as some of them are fundamental to fulfilling the principles of relevance, completeness, consistency, transparency, and accuracy.

As Agrosfär is a tool and not a reporting company, some of the GHG Protocol requirements are not applicable to the tool. Rather the end user of the tool will be responsible for requirements regarding business goals and setting base years. However, the tool should still follow the accounting and reporting principles to enable correct accounting and reporting according to the GHG Protocol. The aim of the Agrosfär calculation model is therefore not to be fully aligned with the Corporate Value Chain (Scope 3) Accounting and Reporting standard, which states inclusion of all relevant scope 3 categories. The standard is aimed at being complied with for selected upstream scope 3 categories in Agrosfär, to the extent it’s possible for a calculation tool. Agrosfär does not measure downstream categories, as the calculation ends at the farm gate.

Appendix table A. Agrosfär compliance with the requirements in the Greenhouse Gas Protocol Corporate Standard and Greenhouse Gas Protocol Agricultural Guidance. Chapter refers to chapter in the Agricultural guidance. NA = not applicable.

Section	**Requirements in Agricultural guidance**	**Shall/ should**	**Compliance Agrosfär**	**Chapter**
GHG Accounting and Reporting Principles	GHG accounting and reporting **shall** be based on the following principles: relevance, completeness, consistency, transparency and accuracy. Trade-offs between the principles should be balanced.	shall	Yes (tool). No (activity data). Assumptions and exclusions are described, and relevant emissions sources are included. For GHG fluxes which are particularly hard to estimate (methane from enteric fermentation), higher Tier methods are applied. To be fully compliant, the farm’s activity data must be included in the review.	3

Business Goals and Inventory Design	Companies **should** have clearly defined goals for managing their GHG fluxes and **should** understand how inventories will allow them to meet those goals.	should	NA (1).	2
Setting Organizational Boundaries	Three ‘consolidation’ approaches can be used to set organizational boundaries: Operational control, Financial control or Equity-share approach.	shall	Yes. The Operational control approach is used for setting organizational boundaries.	5.1
Setting Operational Boundaries	Having set organizational boundaries, companies **should** set operational boundaries for each of their emission sources.	should	Yes, see chapter 2.3 for details on how contract work and leased assets are treated.	5.2
Tracking Emissions Over Time	Companies **shall** establish a base period (BP) against which an organization's performance can be tracked over time. It shall be the earliest point in time for which verifiable emission data are available.	shall	No. A recalculation policy will be included in future versions of the tool (2).	6
	A BP emissions recalculation policy **shall** be in place, and companies shall recalculate the BP inventory to reflect changes in organizational structures. Multi-year base periods are recommended for many agricultural companies.	shall	No. A recalculation policy will be included in future versions of the tool (2).	6
Identifying and Calculating GHG Emissions	The agricultural guidance distinguishes between two types of emissions sources – mechanical and nonmechanical sources (i.e. biological emissions). Companies should first identify the management practices and emissions sources that would need to be reflected in their inventories (see Chapter 4 and Chapter 5) before selecting a calculation approach.	Shall	Yes. Major agricultural nonmechanical sources are included in the Agrosfär tool. Excluded sources are described in chapter 7 and will be included in future versions of the tool.	4 & 7
	The Guidance does not require or recommend the use of a specific calculation approach or tool. Instead, companies **should** select an approach that best meets their objectives for compiling an inventory and that meets the GHG accounting and reporting principles.	should	Yes. The Agrosfär tool mainly applies emission factors based on empirical models to calculate GHG fluxes combined with primary data on farm activity.	7.3

Managing Inventory Quality	When high-quality activity data is not available for all of the emissions sources that need to be included in an inventory, companies **should** prioritize their data collection efforts based on source magnitude.	should	Partially. In the Agrosfär tool, the data required for calculating the emission sources with largest magnitude are prioritized. Future inclusion of upstream emission sources is described in chapter 7. Agrosfär does not include downstream Scope 3 categories. Criteria for prioritizing data collection efforts could be described in a data quality report with an estimation of how much of the overall emissions are captured in the calculations.	7.1-7.2
	When managing inventory quality, companies **should** focus on reducing parameter uncertainty.	should	Partially. It is currently not described in the report how parameter uncertainty is measured in the tool. However, Agrosfär implements limit values to ensure high quality activity data. Automated data collection can also contribute to reducing parameter uncertainty.	7.4
	Information on GHG data uncertainty **should** be reported in inventories.	Should	No. Information regarding uncertainty is not included in the tool currently but might be in future versions, for example as an uncertainty range for calculated results.	7.4
Reporting GHG Emissions	The guidelines state what information companies **shall** publicly report.	shall	NA. The base period is set by the end users of the tool. (2)	9.1
	Companies **shall** publicly report general GHG flux data for all seven GHGs (CO2, CH4, N2O, SF6, PFCs, HFCs and NF3), disaggregated by GHG and reported in units of both metric tonnes and tonnes CO2-equivalent (CO2e).	shall	Yes. CO2, CH4, N2O are reported, HFCs will be included in future versions. The other GHGs are not considered relevant for agriculture.	9.1
	Companies **should** publicly report (for non-mechanical sources): A description of whether the calculation methodologies are IPCC Tier 1, 2, or 3, and a description of how those methodologies were chosen based on the quality criteria in Chapter 7.3.	should	Yes. The IPCC Tier the calculation methodologies followed are described, see chapter 2.6.	9.2
	Companies **should** publicly report Scope 1 emissions disaggregated by mechanical sources, LUC (biogenic CO2 only), and all other non-mechanical sources.	should	No. This is the equivalent of the new categories in LSRG "land use change emissions", "Land management net CO2 emissions" and "Land management non-CO2 emissions". These reporting	9.2

			categories will be included in future versions of the tool.	
Biogenic Carbon	Where LUC results in a reduction in the size of C stocks, the CO2 emissions are reported in Scope 1. Otherwise, all CO2 fluxes are reported outside of the scopes in a separate category ('Biogenic Carbon') that has three components: (1) CO2 fluxes (emissions or removals) during land use management; (2) Sequestration during LUC; and (3) CO2 emissions from biofuel combustion.	should	Partially. Scope 1 LUC will be included in next version of the tool. Biogenic carbon is not included (other than emissions from peat soils), but emissions and sequestration of soil carbon will be included in future versions of the tool and reported according to GHGp LSRG.	9.2

Appendix table B. Agrosfär compliance with the requirements in the Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Accounting and Reporting standard. Chapter refers to chapter in the Scope 3 guidance. NA = not applicable.

Section	**Requirements in Corporate Value Chain (Scope 3) Accounting and Reporting Standard**	**Shall/ should**	**Compliance Agrosfär**	**Chapter**
Accounting and Reporting Principles	GHG accounting and reporting of a scope 3 inventory **shall** be based on the following principles: relevance, completeness, consistency, transparency, and accuracy.	shall	Yes (tool). No (activity data). See table 1 for included categories and justification of exclusions and chapter 2.4. for included emissions and methods for calculating emissions. Agrosfär is a farm-level tool and downstream activities of the farm are out of scope. To be fully compliant, the farm's activity data must be included in the review.	4
Setting the Scope 3 Boundary	Companies **shall** account for all scope 3 emissions and disclose and justify any exclusions. Companies may exclude scope 3 activities included in the minimum boundary of each category provided that any exclusion is disclosed and justified.	Shall	Partially. See table 1 for included categories and justification of exclusions. Future inclusion of upstream emission sources is described in chapter 7. Agrosfär does not include downstream Scope 3 categories.	6
	Companies **shall** account for emissions from each scope 3 category according to the minimum boundaries listed in table 5.4.	shall	Partially. See table 1 for included categories and justification of exclusions. Future inclusion of upstream emission sources is described in chapter 7. Agrosfär does not include downstream Scope 3 categories.	5
	Companies **shall** account for scope 3 emissions of CO2, CH4, N2O, HFCs, PFCs, and SF6 if	Shall	Yes. CO2, CH4 and N2O are the most important farm GHG and are included in the tool. HFCs will be	6

	they are emitted in the value chain.		included in next version of the tool. PFCs, and SF6 are not considered relevant for farm GHG emission calculations.	
	Biogenic CO2 emissions that occur in the value chain **shall** not be included in the scopes but **shall** be included and separately reported in the public report.	Shall	No. Currently biogenic CO2 emissions (other than emissions from peat soils for purchased feed) are not included or reported in the Agrosfär tool.	6
Setting a GHG Target and Tracking Emissions over Time	When companies choose to track performance or set a reduction target, companies **shall**:		NA/Partially. Target setting and base year setting is not set by the tool but by the tool end user. A recalculation policy will be included in future versions of the tool (1, 2).	9
	Choose a scope 3 base year (BY) and specify their reasons for choosing that particular year.	shall	NA	9
	Develop a BY emissions recalculation policy that articulates the basis for any recalculations.	shall	No (2).	9
	Recalculate BY emissions when significant changes in the company structure or inventory methodology occur.	Shall	NA – however Agrosfär will communicate methodological updates in their method reports.	9
Reporting	Companies **shall** publicly report the following information:	shall		9
	A scope 1 and scope 2 emissions report in conformance with the GHG Protocol Corporate Standard	shall	Partially. See Appendix table A “Compliance Corporate standard and Agricultural guidance” for more details. For full compliance, a separate report for scope 1 and 2 should be generated.	11
	Total scope 3 emissions reported separately by scope 3 category.	shall	Partially. Many Scope 3 categories are currently not included in the tool. See table 1 for details. Future inclusion of upstream emission sources is described in chapter 7. Agrosfär does not include downstream Scope 3 categories.	11
	For each scope 3 category, total GHG emissions reported in metric tons of CO2 equivalent, excluding biogenic CO2 emissions and independent of any GHG trades, such as purchases, sales, or transfers of offsets or allowances.	Shall	Partially. Many Scope 3 categories are currently not included in the tool. The ambition of Agrosfär’s calculation model is to be compliant with the Corporate Value Chain (Scope 3) Accounting and Reporting standard for selected upstream scope 3 categories, to the extent it’s possible for a calculation tool. Agrosfär does not measure downstream categories, as the calculation ends at the farm gate.	11
	A list of scope 3 categories and activities included in the inventory.	Shall	Yes. See table 1 for details.	11

	A list of scope 3 categories or activities excluded from the inventory with justification for their exclusion.	Shall	Yes. See table 1 for details	11
	Base year (BY): the year chosen as the scope 3 BY; the rationale for choosing the BY; the BY emissions recalculation policy; scope 3 emissions by category in the BY, consistent with the BY emissions recalculation policy; and appropriate context for any significant emissions changes that triggered BY emission recalculations.	Shall	NA/Partially. Target setting and base year setting is not set by the tool but by the tool end user. Recalculation policy will be included in future versions of the tool (1, 2).	11
	For each scope 3 category, any biogenic CO2 emissions are reported separately.	shall	No. Biogenic emissions are currently not included in the tool but will be included in future versions of Agrosfär.	11
	For each scope 3 category, a description of the types and sources of data, including activity data, emission factors and GWP values, used to calculate emissions, and a description of the data quality of reported emissions data.	shall	No. Emission factors used to calculate scope 3 emissions are not presented in the report. Activity data is collected from several farm databases (primary farm data) (see chapter 2.2). Displaying of activity data has been considered for future versions of Agrosfär.	11
	For each scope 3 category, a description of the methodologies, allocation methods, and assumptions used to calculate scope 3 emissions.	shall	Partially. This is described in chapter 3, 5 and 6. Many Scope 3 categories are currently not included in the tool. Future inclusion of upstream emission sources is described in chapter 7. Agrosfär does not include downstream Scope 3 categories.	11
	For each scope 3 category, the percentage of emissions calculated using data obtained from suppliers or other value chain partners.	shall	No. Currently not included in the tool, this could be done on farm level calculations and might be incorporated in future versions of the tool.	11

(1) Agrosfär is a tool for climate accounting on farms, both on a product level and for the entire farm. Most of Agrosfär's customers set climate targets and a base year for their respective operations and value chains. Agrosfär is an enabler of climate accounting, and setting targets and a base year is therefore not relevant to Agrosfär. Agrosfär will, however, enable follow ups on customers climate targets, in relation to base year and target year.

(2) A description of recalculation policy for the base year will be added in the next version of Agrosfär, when Agrosfär is able to follow up results from year to year.

Appendix 2: Organic soils

Drained organic soils are a source of CO2 and N2O emissions due to oxidation induced by drainage. These emissions should, according to most guidelines, be included in life cycle assessment. According to PEFCR, CO2 emissions from drained organic soils shall be included based on a model that relates the drainage levels to annual carbon oxidation (European Commission, 2018). In PEFCR, dairy minimum requirements are described and are based on IPCC Tier 1: Hectares of managed or drained organic soils multiplied by a default emission factor (European Dairy Association, 2018). In the current tool, the minimum requirements according to PEFCR dairy are followed as information on drainage level is not a datapoint which is currently collected, and no easily available model relating drainage level to CO2 emissions is known to us but is a possible future improvement of the tool/model.

Emission factors

The emission factors for organic soil (Appendix table C) applied in the tool are in line with the emission factors used in the Swedish national inventory (Naturvårdsverket 2021a; 2021b). For cropland, the CO2 emission factor is derived from IPCC Wetland supplement, further referred to as IPCC WL GL (IPCC, 2014) but reworked by Lindgren & Lundblad (2014) to only include result from countries with similar climatic conditions as Sweden. The emission factor for CO2 is therefore somewhat lower than the default IPCC Tier 1 emission factor. For N2O emissions from cropland on organic soil, the emission factor is derived from IPCC without adjustments. The grassland emission factors originate from IPCC WL GL, but instead of using the default grassland emission factors, emission factors for forest are used. Swedish grasslands are often semi-natural pastures, and are very rarely fertilised or intensively grazed. Whereas the studies upon which the IPCC grassland emission factors are derived are based on countries with intensively managed grasslands. Emissions from Swedish grasslands are, therefore, more likely to be in line with forest land emissions than intensively managed grassland (Lindgren & Lundblad, 2014)

Appendix table C. Emission factors for cropland and grassland on organic soil.

Land use category	Climate	Nutrient status	ton CO2-C/ha/year	kg N2O-N/ha/year
Cropland			6,1	13
Grassland	Boreal	Rich	0,93	3,2
	Boreal	Poor	0,25	0,22
	Temperate	Rich	2,6	2,8
	Temperate	Poor	2,6	2,8

Definition of organic soils

The definition of organic soil is complex and does not only regard organic matter content but also the thickness of the soil layer, clay content, water saturation, underlying material, and origin. IPCC doesn't provide a definition of organic soil, instead it follows the FAO definition. The FAO definition of organic soils (Food and Agriculture Organization of the United Nations (FAO), 1998) (FAO, 1998) can, as a simplification, be described using 3 criteria: 1) the soil must have a thickness of at least 10 cm; 2) soils which are never water saturated should have at least 35% organic matter (OM) (by weight); and 3) for soils which are subject to water saturation and have no clay, they should have at least 20% OM, or if the soil has more than 60% clay, it should have at least 30% OM. For a soil to be classified as organic, either criterion 1 and 2 must be fulfilled or criterion 1 and 3. IPCC mostly follows the FAO definition, excluding the thickness criterion, allowing countries to be able to use their own historical definitions of organic soil. The definition of organic soil differs between countries and disciplines, especially with respect to the minimum requirement of organic matter (IPCC, 2014).

A consequence of this is that countries reporting to UNFCCC can use either country specific definitions or the IPCC/FAO definition, which complicates the decision of how to define organic soil in this tool. When reporting to UNFCCC, Sweden is compliant with the FAO definition (Lindahl & Lundblad, 2021), but several national definitions also exist in parallel. As an example, in the Swedish soil classification system, soil with an OM content >30% is classified as organic soil. The 30% limit is derived from Swedish Jordartsnomenklatur from 1953 (Lindahl & Lundblad, see Jordartsnomenklatur 1953). An exception is the typical Swedish “gyttja” soils, which are a group of soils for which the criterion is at least 6% OM. As Sweden follows the FAO definition of organic soils when reporting to UNFCCC, some of the gyttja soils not fulfilling the FAO definition are excluded in the national inventory report (Lindahl & Lundblad, 2021). Further, in soil mapping of agricultural land, a soil with >40% OM is classed as organic soil and as mineral blended organic soil if OM is 20-40% (Jordbruksverket, 2010)

Method in Agrosfär

In this tool, the criterion for organic soil is set to 40% OM for drained soils. The 40% limit is based on the level of information available from the set intervals used in Markkartering. Those intervals are further transferred to DataVäxt, meaning that no values below 40% OM are registered as organic soil in DataVäxt. This approach is considered a simplified but pragmatic definition choice.

The emission from organic soils is estimated using the following equation:

$$CO2 - C, or\ N2O - N\ on\ site = \sum_{c,n} A * EF$$

Where:

A= land area of drained organic soil in a land use category in climate domain c and nutrient status n, ha.

EF= emission factors for drained organic soils, by climate domain c and nutrient status n, n, tonnes C/ha/year or kg N/ha/year.

The area (A) is derived following either one of three options: 1) if soil mapping data is available on a field level with several datapoints, the field will be proportionally divided into % of land classified as organic soil as the % of datapoints exceeding 40% OM. If 5 out of 10 datapoints > 40% OM, 50 % of the total field area will be classified as organic soil; 2) if there is only one datapoint at the field level, the whole field will be categorised according to this datapoint; or 3) if no soil sampling data is available, a manual choice can be made.

Uncertainties

The largest uncertainties coupled to the calculation of emissions from organic soil are as follows:

1) The definition of organic soils varies between countries and even within countries depending on purpose; however, organic soil has a large impact on the CF and, thus, how we define organic soils has a large impact on the results.
2) For emission factors, the uncertainty ranges are quite large; for example, N2O-N has an uncertainty range between 8,2 – 18 (compared to the EF of 13 kg N2O-N/ha/yr).
3) Characteristics of the emissions: The emissions are not constant nor linear to the water table (WT) level. Emissions of CO2 increase with increased depth of water table level, Whereas N2O is not as dependent on WT.
4) National emission factors vs local prerequisites: The IPCC emission factors are suited for national level calculations; For example, Tiemeyer et al. (2020) found that their modelled and aggregated implied emission factor, which considered high resolution data on type of organic soil and mean annual water table level for German organic soils, aligned quite well with the IPCC Tier 1 emission factors. However, on a field level, these emission factors might give misguided results as the emissions depend on parameters which can vary largely on a local level.

Appendix 3: Crop production – Equations

Emissions from seed production

$$CI_{seed} = A \times \sum_n SI_n \times EFseed_n$$

Equation 3. 1

Where:

CI_{seed}= Climate impact for production of used seed, [kg CO_2], [kg N_2O] and summarised as [kg CO_2-eq.]

A= Area of field [ha]

SI_n= Input of seed type *n* [kg/ha]

$EFseed_n$= Emission factor of seed type *n,* [kg CO_2/kg], [kg N_2O /kg] and summarised as [kg CO_2-eq./kg]

Fertilisers and lime production

$$CI_{fert.prod} = A \times \sum_n FI_n \times EFfertilizer_n$$

Equation 3. 2

$$CI_{lime.prod} = \frac{A \times \sum_n LI_n \times EFlime.prod_n}{y}$$

Equation 3. 3

Where:

$CI_{fert.prod}$= Climate impact for production of applied fertiliser [kg CO_2], [kg N2O] and summarised as [kg CO_2-eq.]

$CI_{lime.prod}$= Climate impact for production of applied lime, [kg CO_2-eq.]

A= Area of field [ha]

FI_n= Application ratio of fertiliser type *n* [kg/ha]

LI_n= Application ratio of lime type *n* [kg/ha]

$EFferlilizer_n$= Emission factor of fertiliser type *n,* [kg CO_2/kg], [kg N_2O/kg] and summarised as [kg CO_2-eq./kg]

$EFlime.prod_n$= Emission factor of lime type *n,* [kg CO_2-eq./kg]

y= Number of years between liming

Field emissions from lime application

$$CI_{CO2\ from\ lime} = \frac{A \times \sum_n (LI_n \times EFlime_n) \times \frac{44}{12}}{y}$$

Equation 3. 4

Where:

$CI_{CO2\ from\ lime}$= Climate impact from CO_2 emissions in field from liming, [kg CO_2]

A= Area of field [ha]

LI_n= Application ratio of lime type n [kg/ha]

$EF\ lime_n$= Emission factor [kg C/kg], 0.12 for calcic limestone and 0.13 for calcic dolomite and Mg-lime (Naturvårdsverket, 2021a)

$\frac{44}{12}$= Recalculation factor from kg elemental C to kg CO_2

y= Number of years between liming

Production of crop protection

$$CI_{crop\ protecion} = A \times \sum_n CPI_n \times EFcrop\ protection_n$$

Equation 3. 5

Where:

$CI_{crop\ protecion}$= Climate impact for production of used crop protection, [kg CO_2-eq.]

A= Area of field [ha]

SI_n= Input of crop protection type n [kg/ha]

$EFcrop\ protection_n$= Emission factor of crop protection type n, [kg CO_2-eq./kg]

Field work

$$CI_{field\ work} = A \times \sum_n FI_n \times EFfuel_n$$

Equation 3. 6

Where:

$CI_{field\ work}$= Climate impact for field work, [kg CO_2-eq.]

A= Area of field [ha]

FI_n= Consumption of fuel type n, [l/ha] or [m^3/ha]

$EFfuel_n$= Emission factor of fuel type n, [kg CO_2-eq./l] or [kg CO_2-eq./m^3] (well -to-wheel)

Direct N_2O emissions from mineral soils

$$CI_{N20\,diretct} = CI_{N20\,\min fert} + CI_{N20\,org\,fert} + CI_{N20\,residues}$$

Equation 3. 7

Where:

$CI_{N20\,min\,fert}$= Climate impact from direct N_2O emissions from mineral fertiliser, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 8)

$CI_{N20\,org\,fert}$= Climate impact from direct N_2O emissions from manure and organic fertiliser, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 9)

$CI_{N20\,residues}$= Climate impact from direct N_2O emissions from crop residues, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 10)

Emissions from applied mineral fertiliser, manure and organic fertiliser

$$CI_{N20\,min\,fert} = A \times \sum_n Nmin.fert_n \times EF_{N20-N\,MF} \times \frac{44}{28} \times GWP_{N20}$$

Equation 3. 8

$$CI_{N20\,org\,fert} = A \times \sum_n Norg.fert_n \times EF_{N20-N} \times \frac{44}{28} \times GWP_{N20}$$

Equation 3. 9

Where:

$CI_{N20\,min\,fert}$= Climate impact from direct N_2O emissions from mineral fertiliser, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

$CI_{N20\,org\,fert}$= Climate impact from direct N_2O emissions from manure and organic fertiliser, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

A= Area of field [ha]

$Nmin.fert_n$= Application ratio of N in mineral fertiliser type n [kg/ha]

$Nmin.fert_n$= Application ratio of N in manure or organic fertiliser type n [kg/ha]

EF_{N2O-N}= Emission factor for N in fertiliser and manure [kg N_2O–N /kg N], set to 1% for all types of fertiliser, manure and crop residue (aggregated emission factors in IPCC 2019 Tier 1, table 11.1)

$\frac{44}{28}$= Recalculation factor from kg N_2O–N to kg N_2O

GWP_{N20}= Global Warming Potential 100 y for N_2O, [kg CO_2-eq./kg N_2O] set to 273 according to IPCC AR6, 2021

Emissions from crop residues

$$CI_{N20\,residues} = \left((AGR_{DM} \times N_{AG} \times (1 - Frac_{Remove}) \times EF_{N20-N}) + (BGR_{DM} \times N_{BG} \times EF_{N20-N})\right) \times A \times \frac{44}{28} \times GWP_{N20}$$

Equation 3. 10

Where:

$CI_{N20\,residues}$= Climate impact from direct N_2O emissions from crop residues, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

AGR_{DM}= Above ground residue [kg dry matter/ha] (Equation 3. 11$AGR_{DM} = Y_{DM} \times Slope_n + Intercept_n$

Equation 3. 11)

N_{AG}= Nitrogen fraction in above-ground crop residues (IPCC 2019, table 11.1A)

$Frac_{Remove}$= Fraction of above-ground residues removed [mass %]. Fraction removed can be reported as a specific figure in Agrosfär or as a Yes/No question. Yes = 50% of crop residues are considered removed. N_o =0% crop residues are considered removed.

EF_{N2O-N}= Emission factor for N in fertiliser and manure [kg N_2O–N /kg N], set to 1% for all types of fertiliser, manure and crop residue (aggregated emission factors in IPCC 2019 Tier 1, table 11.1

BGR_{DM}= Below ground residue [kg dry matter/ha] (Equation 3. 12)

N_{BG}= Nitrogen fraction in below-ground crop residues (IPCC 2019, table 11.1A)

A= Area of field [ha]

$\frac{44}{28}$= Recalculation factor from kg N_2O–N to kg N_2O

GWP_{N20}= Global Warming Potential 100 y for N_2O, [kg CO_2-eq./kg N_2O] set to 273 according to IPCC AR6, 2021

Above ground crop residues as stated in IPCC 2019, table 11.2:

$$AGR_{DM} = Y_{DM} \times Slope_n + Intercept_n$$

Equation 3. 11

Where:

AGR_{DM}= Above ground residue [kg dry matter/ha]

Y_{DM}= Dry matter yield of harvested crop [kg dry matter/ha]. Dry matter yield can be reported in Agrosfär. If only fresh yield of harvested crop is reported the dry matter yield can be calculated using the Dry matter fraction of harvested product for the crop according to IPCC 2019, table 11.1A

$Slope_n$= Slope of crop type n [-] according to IPCC 2019, table 11.2

$Intercept_n$= Intercept of crop type n [kg dry matter/ha] according to IPCC 2019, table 11.2

Below ground crop residues: as stated in IPCC 2019, table 11.2:

$$BGR_{DM} = AGR_{DM} \times RS_n$$

Equation 3. 12

Where:

BGR_{DM}= Below ground residue [kg dry matter/ha]

AGR_{DM}= Above ground residue [kg dry matter/ha] (Equation 3. 11)

RS_n= Ratio of below-ground biomass to above-ground biomass of crop type n [-] according to IPCC 2019, table 11.1A

Indirect N_2O emissions

$$CI_{N20\ indiretct} = CI_{N20\ ind_{leach}} + CI_{N20\ AV}$$

Equation 3. 13

Where:

$CI_{N20\ ind_{leach}}$ = Climate impact from indirect N leaching/runoff, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 14)

$CI_{N20\ AV}$ = Climate impact from ammonium volatilisation and redeposition, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 22)

Indirect N_2O due to N leaching/run-off

$$CI_{N20\ ind_{leach}} = A \times EF_{N2O-N} \times \frac{44}{28} \times GWP_{N20} \times \left(\left(N_{leach\ std} \times \left(1 + F_{leach\ crop,n}\right)\right) \times \left(F_{leach\ till,n} + F_{leach\ till,n} \times \left(F_{leach\ c_{crop},n} - 1\right)\right) + N_{leach\ manure}\right)$$

Equation 3. 14

Where:

$CI_{N20\ ind_{leach}}$ = Climate impact from indirect N leaching/runoff, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

A= Area of field [ha]

EF_{N2O-N}= Emission factor for leaching/runoff from [kg N_2O–N /kg N], set to 1.1% in IPCC 2019 Tier 1, table 11.3

$N_{leach\ std}$= Standard N leaching from field n, [kg N/ha] (Equation 3. 15)

$F_{leach\ crop,n}$= Adjustment factor for crop n, [-] (Equation 3. 16)

$F_{leach\ till,n}$= Tilling time reduction factor for field n, [-] (Equation 3. 17)

$F_{lleach\ c_{crop},n}$= Catch crop reduction factor for field n, [-] (Equation 3. 18)

$N_{leach\ man_{type},n}$ = Basic leaching of application of manure type n on soil type n, [kg N/ha] (Equation 3. 19)

$\frac{44}{28}$= Recalculation factor from kg N_2O–N to kg N_2O

GWP_{N20}= Global Warming Potential 100 y for N_2O, [kg CO_2-eq./kg N_2O] set to 273 according to IPCC AR6, 2021

$$N_{leach\ std} = VLOOKUP\left(Municip_n; STDleach_{table\left(MATCH\left(Soil_{type_n}\right)\right)}\right)$$

Equation 3. 15

Where:

$N_{leach\ std}$= Standard N leaching from field n, [kg N/ha]

$Municip_n$= Name of municipality where field n is situated

$STDleach_{table}$= Table with standard leaching data according to Aronsson and Torstensson (2004)

$Soil_{type_n}$= Name of soil type of field n

$$F_{leach\ crop,n} = VLOOKUP(Crop_n; Cropleach_{table})$$

Equation 3. 16

Where:

$F_{leach\ crop,n}$= Adjustment factor for crop n, [-]

$Crop_n$= Name of crop type n

$STDleach_{table}$= Table with crop leaching factors from Odlingsperspektiv

$$F_{leach\,till,n} = VLOOKUP\left(Till_{time_n}; Till_{time_{table(MATCH(Crop_n))}}\right)$$

Equation 3. 17

Where:

$F_{leach\,till,n}$= Tilling time reduction factor for field n, [-]

$Till_{time_n}$= Time for tilling after harvest in field n, [m-d]

$Till_{time_{table}}$= Table with tilling time reduction factor from Odlingsperspektiv

$Crop_n$= Name of crop in field n

$$F_{leach\,c_{crop},n} = VLOOKUP\left(Crop_{type_n}; C_{crop_{table\left(MATCH\left(Till_{time_n}\right)\right)}}\right)$$

Equation 3. 18

Where:

$F_{lleach\,c_{crop},n}$= Catch crop reduction factor for field n, [-]

$Crop_{type_n}$= Name of type of crop in field n

$C_{crop_{table}}$= Table with catch crop reduction factor from Odlingsperspektiv

$Till_{time_n}$= Time for tilling after harvest in field n, [m-d]

$$N_{leach\,man_{type},n} = VLOOKUP\left(Man_n; Man_{s_{table\left(MATCH\left(Soil_{type_n}\right)\right)}}\right) \times TM_n$$

Equation 3. 19

$$F_{leac\,man_{time},n} = VLOOKUP\left(Man_n; Man_{t_{table\left(MATCH\left(Crop_{type_n}; Ap_{t_n}\right)\right)}}\right)$$

Equation 3. 20

$$N_{leach\,manure} = \sum\nolimits_n \left(N_{leach\,man_{type},n} \times F_{leac\,man_{time},n}\right)$$

Equation 3. 21

Where:

$N_{leach\,man_{type},n}$ = Basic leaching of application of manure type n on soil type n, [kg N/ha]

Man_n= Name of manure in field n

$Man_{s_{table}}$= Table with basic leaching data from manure type vs. soil type from Odlingsperspektiv

$Soil_{type_n}$= Name of soil type in field n

TM_n= Applied tonnage of manure in field n [ton/ha]

$F_{leac\ man_{time},n}$= Application factor of manure n at application time n

$Man_{t\quad table}$= Application factor manure type vs. type of crop and application time from Odlingsperspektiv

Ap_{t_n}= Application time of manure in field n

$N_{leach\ manuse}$ = Leaching from application of manure, [kg N/ha]

Indirect N_2O due to ammonium volatilisation

$$CI_{N20\ AV} = A \times EF_{N2O-NH3} \times \frac{44}{28} \times GWP_{N20} \times \left(AV_{NH3-N\ min\ fert} + AV_{NH3-N\ man}\right)$$

Equation 3. 22

Where:

$CI_{N20\ AV}$ = Climate impact from ammonium volatilisation and redeposition, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

A= Area of field [ha]

EF_{N2O-N}= Emission factor for volatilisation and redeposition from [kg N_2O–N /kg NH3-N], set to 1.0% in IPCC 2019 Tier 1, table 11.3

$\frac{44}{28}$= Recalculation factor from kg N_2O–N to kg N_2O

GWP_{N20}= Global Warming Potential 100 y for N_2O, [kg CO_2-eq./kg N_2O] set to 273 according to IPCC AR6, 2021

$$AV_{NH3-N\ min\ fert} = \sum_n Nmin.fert_n \times EF_{NH3-N\ MF}$$

Equation 3. 23

Where:

$AV_{NH3-N\ min\ fert}$= Ammonium volatilisation from applied N in mineral fertiliser, [kg NH_3-N/ha]

$Nmin.fert_n$= Application ratio of N in mineral fertiliser type n [kg/ha]

$EF_{NH3-N\ MF}$= Emission factor for N in fertiliser and manure [kg NH_3–N/kg N], set to 1.2%, average value according to Swedish NIR 2021

$$AV_{NH3-N\ man} = \times \sum_n \left(Nman_n \times R_{NH-N\ Man,n} \times \right.$$

$$\left. VLOOKUP\left(Man_n; Man_{Av_{table\left(MATCH\left(MS_{tech_n}; MS_{time_n}; Ap_{t_n}\right)\right)}} \right) \right)$$

Equation 3. 24

Where:

$AV_{NH3-N\ man}$= Ammonium volatilisation from applied N in manure, [kg NH_3-N/ha]

$Nman_n$= Application ratio of N in manure type n [kg/ha]

$R_{NH-N\ Man,n}$= NH–N/ N rate in manure type n, [kg NH–N /kg N]

Man_n= Name of manure type n

$Man_{Av_{table}}$= Table with N-loss data from manure type in relation to timing, spreading technique and how fast manure is incorporated into soil after spreading from Karlsson & Rhode (2002), [kg NH_3-N /kg NH-N]

MS_{tech_n}= Name of spreading technique of manure type n

MS_{time_n}= Time of incorporation into soil after spreading of manure type n

Ap_{t_n}= Application time of manure in field n

Emissions from organic soils

$$CI_{Org} = CI_{Org_{N2O}} + CI_{Org_{CO2}}$$

Equation 3. 25

Where:

CI_{Org} = Total climate impact from organic soils, [kg CO_2-eq.]

$CI_{Org_{N2O}}$ = Climate impact from N_2O emission from organic soils, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation) (Equation 3. 26)

$CI_{Org_{CO2}}$ = Climate impact from CO_2 emission from organic soils, [kg CO_2-eq.] (Equation 3. 27)

$$CI_{Org_{N2O}} = IF\left(Mulch > 40\%\ ; A \times EF_{Org_{N2O-N}} \times \frac{44}{28} \times GWP_{N2O}; 0 \right)$$

Equation 3. 26

Where:

$CI_{Org_{N2O}}$ = Climate impact from N_2O emission from organic soils, [kg CO_2-eq.] and as [kg N_2O] (removing GWP from equation)

$Mulch$= Mulch content in soil [mass-%]

A= Area of field [ha]

$EF_{Org_{N2O-N}}$=Emission factor for N_2 O emission from organic soils [kg N_2O–N/ha,y], set to 13 in Swedish NIR 2021, Annex 1 pg 136-137

$\frac{44}{28}$= Recalculation factor from kg N_2O–N to kg N_2O

GWP_{N2O}= Global Warming Potential 100 y for N_2O, [kg CO_2-eq./kg N_2O]
set to 273 according to IPCC AR6, 2021

$$CI_{Org_{CO2}} = IF\left(Mulch > 40\%\,; \mathrm{A} \times \left(EF_{Org_{CO2_{atm}}} + EF_{Org_{CO2_{diss}}}\right) \times \frac{44}{12}; 0\right)$$

Equation 3. 27

Where:

$CI_{Org_{CO2}}$ = Climate impact from CO_2 emission from organic soils, [kg CO_2-eq.]

$Mulch$= Mulch content in soil [mass-%]

A= Area of field [ha]

$EF_{Org_{CO2_{atm}}}$=Emission factor for CO_2 loss to the atmosphere from organic soils [kg CO_2–C/ha,y], set to 6100 in Swedish NIR 2021, Annex 1 pg. 136-137

$EF_{Org_{CO2_{atm}}}$=Emission factor for loss of dissolved carbon from organic soils [kg CO_2–C/ha,y], set to 120 in Swedish NIR 2021, Annex 1 pg. 136-137

$\frac{44}{12}$= Recalculation factor from kg CO_2–C to kg CO_2

Crop drying

$$CItot_{dry} = \sum_{n} CFdry_n \times EFfuel_n + \sum_{m} CEdry_m \times EFel_m$$

Equation 3. 28

$$CItot_{dry} = A \times Y_{fresh} \times \left(SCFdry \times \left(\frac{1 - DMwet}{1 - DMdry}\right) \times EFfuel_n + SCEdry \times EFel_m\right)$$

Equation 3. 29

Where:

$CItot_{dry}$= Total climate impact for drying, [kg CO_2-eq.]

$CFdry$= Measured fuel consumption of drying, [MWh].

$EFfuel_n$= Emission factor of fuel type n, [kg CO_2-eq./MWh]

$CEdry$= Measured electricity consumption of drying, [MWh]

$EFel_n$= Emission factor of electricity source m, [kg CO_2-eq./MWh]

A_n= Area of field [ha]

Y_{fresh}= Fresh Yield of harvested crop [ton/ha]

$SCFdry$= Standard fuel consumption of drying, [MWh/ton water]. Set to 0.14 based on the assumption that it takes 0.15 l of fuel oil to dry 1 kg of water

$DMwet$= Dry matter in crop before dryer [mass fraction]

$DMdry$= Dry matter in crop after dryer [mass fraction]

$SCEdry$= Standard electricity consumption of drying, [MWh/ton crop], set to 0.019

Appendix 4: Animal husbandry-Equations

Energy requirement – Cows

The energy requirement is estimated based on the Norfor system (Volden, 2011).

Total net energy requirement, NEL (MJ NE per head and day), of cows is estimated per head and day as:

$$NEL = NEL_{maint} + NEL_{gest} + NEL_{gain} + NEL_{milk} \tag{Equation 4. 1}$$

NEL_{maint} is estimated as in Equation 4. 2, NEL_{gest} as in Equation 4. 3, NEL_{gain} as in Equation 4. 4 and NEL_{milk} as in Equation 4. 5.

The energy requirement for maintenance, NEL_{maint} (MJ NE per head and day), is calculated as:

$$NEL_{maint} = k_m \times BW^{0.75} \times exercise \tag{Equation 4. 2}$$

Where:

$k_m =$ 0.29256

$BW =$ Current body weight (kg)

$Exercise =$ Factor to describe requirement for activity. Loose and grazing = 1.1. Tied up = 1.0.

The energy requirement for pregnancy, NEL_{gest} (MJ NE per head and day), for cows and heifers is calculated as:

$$NEL_{gest} = \frac{BW_{mat}}{600} \times e^{k_g \times gest_{day} - m_g} \tag{Equation 4. 3}$$

Where:

$BW_{mat} =$ Mature body weight (kg). Default value per breed from Norfor (2022).

$Gest_{day} =$ Day in gestation (day).

$k_g =$ 0.0144

$m_g =$ 1.1595

If last insemination prior to calving is known (for example if last insemination occurred during the period studied), then $Gest_{day}$ day n prior to calving is calculated as:

$Gest_{day_n}$ = Date day (n) – Date last insemination

If the date for calving is known, but the date for last insemination prior to calving is unknown (for example, if the cow was bought pregnant) then $Gest_{day}$ day n prior to calving is calculated as:

$Gest_{day_n}$ = 284 – (Date calving - Date day (n))

Where:

284 is the typical number of days of pregnancy (Volden, 2011, chapter 9.1.3)

Energy requirement for weight gain, NEL_{gain} (MJ NE) per cow and day, is calculated as:

$$NEL_{gain} = 0.00145 \times BW + 12.48 \times gain + 0.68 \qquad \text{Equation 4. 4}$$

This is only calculated if $gain > 0$.

Where:

$BW =$ Current body weight (kg)

$Gain =$ Weight gain (kg/day)

Energy requirement for milk production, NEL_{milk} (MJ NE) per cow and day, is calculated as:

$$NEL_{milk} = k_m \times ECM \qquad \text{Equation 4. 5}$$

Where:

$k_m =$ 3.14

$ECM =$ Milk production expressed as Energy Corrected milk (kg ECM per day)

Milk yield can be expressed in different units, kg milk, kg ECM and kg FPCM. ECM (kg) shall be used for estimations of energy requirements and is calculated as:

$$ECM = yield_{milk} \times (0.25 + 0.122 \times Fat_{perc} + 0.077 \times Protein_{perc}) \qquad \text{Equation 4. 6}$$

Where:

$yield_{milk}$ = Milk yield (kg milk)

fat_{perc}= Percentage fat

$protein_{perc}$= Percentage protein

The following hierarchy is applied:

1. Use ready data on milk yield expressed as kg ECM.
2. IF kg ECM is unknown and the milk yield is expressed as kg milk, then recalculations are needed based on fat and protein content [%] of the milk:
    a. Farm-specific data on fat and protein content, e.g. annual average
    b. Default values depending on breed of the cow
    c. If breed is unknown or default values for the breed are unknown, use general default values: 4.2% fat and 3.4% protein

The unit "kg FPCM" is seen in international papers and in LCA. FPCM stands for Fat and protein corrected milk. Roughly, 1 kg ECM equals 1.0076 to 1.0080 kg FPCM, and is calculated as:

$$FPCM = yield_{milk} \times (0.2534 + 0.1226 \times Fat_{perc} + 0.0776 \times Protein_{perc}) \qquad \text{Equation 4. 7}$$

Dairy cows:

The energy requirement and feed intake of a dairy cow is much higher during lactation (when the cow produces milk) than during the dry period (the period prior to calving when the cow does not produce milk). In addition, the feed ration differs between lactating cows (concentrates and forage) and dry cows (only/mainly forage). The net energy requirement of lactating cows and dry cows must be estimated separately. Hence, the milk yield shall only be given for the lactation period. The more detailed data on milk yield, the better the estimate of energy requirement.

The following hierarchy is used to identify the milk yield of dairy cows:

i) Measured milk yield (kg milk or kg ECM) per cow per day.

ii) Measured milk yield (kg milk or kg ECM) per cow per year. Kg ECM per day in lactation is then calculated as; kg ECM per year/number of days in lactation per year

The lactation period (date at the start of the period, date at the end of the period, and length of the period) must be determined:

1. Date at the start of the lactation period = the day the cow calves.
2. Date at the end of the lactation period:
    - If the cow becomes pregnant after birth: If the length or the end of the lactation period is unknown, the "end date" is estimated as 60 days prior to calving.
      If the date for calving is unknown (e.g. if the calf is born next year) but the day in gestation is known, then the end

  date is set to Gest_{day} 224 (284 days in gestation – 60 days dry period).
  If the date for calving and $gest_{day}$ is unknown, the length of the lactation period is assumed to be 305 days.

- If the cow does not become pregnant again after giving birth, the cow is assumed to produce milk until the day it leaves the farms.

iii) Milk (kg milk or kg ECM per year) delivered to dairies. Kg ECM per cow and day in lactation is then calculated as: The average milk yield per cow and day in lactation is estimated based on number of cows, average lactation period (305 days) and on-farm consumption of milk for calves, etc. As default, on-farm consumption of milk is assumed to be 10% of the milk yield for organic production and 3.5% for conventional production.

Appendix table D. Beef cows: There is little data on milk yield for suckler/beef cows, and we can´t expect farm-specific data. Some estimates are 1500 -2000 kg milk per cow and year. The following default values are suggested for Agrosfär (total 2000 kg milk per year). Data comes from Bertilsson (2016), and refers to a cow that weighs 750 kg:

Month	Days after calving	kg ECM per cow and day
1	0-30	14
2	31-60	12
3	61-90	12
4	91-120	10
5	121-150	10
6	151-180	8

Assumption: These default values are assumed to be valid for any breed. In practice, the yield may differ. However, NEL_{milk} contributes to a limited share of total NEL of beef cows.

Weight and weight gain – Growing cattle

Current weight and weight gain is estimated as in Norfor (Volden, 2011, chapter 3.2.1). Current weight day n is estimated as ((Volden, 2011, eq 3.5):

$$BW_{calc} = BW_{start} \times e^{\left(A \times \left(1 - e^{\left(-B \times (Age - Age_{start})\right)}\right)\right)}$$

Equation 4. 8

Where:

BW_{calc} = current body weight (kg), day n

$Age =$ current age (days), day n

$Age_{start} =$ age (days) at the start

$BW_{start} =$ body weight (kg) at the start

The start point is always set to the birth of the animal. If a weight recording exists at the date of birth, BW_{start} is set to the weight at that given date. If no such weight recording exists, BW_{start} is set to a default value from Norfor (Norfor, 2022). The default value is dependent on breed and sex (heifer, bull, steer). Age_{start} is always 0, the age in days at birth.

A and B = factor that are calculated as (Volden, 2011, eq 3.7-3.8):

$$A = \ln\left(BW_{mat} \times \frac{1.1}{BW_{start}}\right)$$ Equation 4. 9

$$B = \frac{\ln\left(\frac{\mathrm{A}}{\ln\left(BW_{mat} \times \frac{1.1}{BW_{end}}\right)}\right)}{(Age_{end} - Age_{start})}$$ Equation 4. 10

Where:

$BW_{mat} =$ body weight as mature (kg). Default values per breed and sex (Norfor, 2022)

$BW_{end} =$ body weight (kg) at the end of the rearing period

$Age_{end} =$ age (days) at the end of the rearing period

The following hierarchy is applied to determine BW_{end} and Age_{end} :

- Heifers:
    1. Heifers with a known calving date: $BW_{end}$is set to $BW_{mat} - 100$ and Age_{end} = calving date. This ensures that the formula for calculating body weight is continuous as the heifer turns into a cow. In other words, the body weight formula for heifers gives the same result as the body weight formula for cows on the calving date.
    2. Heifers without a known calving data: $BW_{end}$is set to $BW_{mat} - 100$. Age_{end} = default value for age at first calving, i.e., 793 days for dairy breeds (26 months*30.5 days per month) and 732 days for beef breeds (24 months*30.5 days per month)
- Bulls and steers:

1. Use intermediate data, for example, from weighing of the animal during the rearing period or when the animal is sold. Only the most recent weighing data is used, and only if either of the following two conditions are met:
    a. The animal has not left the farm.
    b. The animal has left the farm and the weighing occurred recently enough. The weighing is considered recent if it is within the last 25% of the time period between the animal's arrival and departure.
2. Use default values based on average slaughtering data.
    a. Bulls: BW_{end} = 60% of BW_{mat}, and Age_{end} = 549 days (18 months)
    b. Steers: BW_{end} = 80% of BW_{mat}, and Age_{end} = 915 days (30 months)

The daily weight gain (kg per day), DG_{calc}, day n is estimated as:

$$DG_{calc}\ (day\ n) = BW_{calc}\ (day\ n + 1) - BW_{calc}\ (day\ n)$$ Equation 4. 11

Energy requirement – Growing cattle

The net energy requirement, NEG (MJ NE per growing cattle and day), for growing cattle is estimated as:

$$NEG = NEG_{maint} + NEG_{gain} + NEG_{gest}$$ Equation 4. 12

NEG_{maint} is estimated as in Equation 4. 13, and NEG_{gain} as in Equation 4. 14 – Equation 4. 26. NEG_{gest} is only estimated for pregnant heifers, as in Equation 4. 3.

Energy requirement for maintenance, NEG_{maint} (MJ NE) per growing cattle and day, is calculated as:

$$NEG_{maint} = NEG_{maint,k} \times BW^{0.75} \times exercise$$ Equation 4. 13

$NEG_{maint,k}$ is assumed to be (Åkerlind, M. pers comm. 2022):

- Heifers and steers, any breed = 0.376
- Bulls of dairy breeds and crossbreeds = 0.381
- Bulls of beef breeds = 0.418

$Exercise =$ factor to describe requirement for activity. (Åkerlind, M. pers comm. 2022).

- Loose and grazing = 1.1
- Tied up = 1.0

Energy requirement for weight gain, NEG_{gain} (MJ NE) per growing cattle and day, is calculated as (Volden, 2011, eq 9.5):

$$NEG_{gain} = \frac{\left(\left(22.9\ \times gain_{prot} + 39.3\ \times gain_{fat}\right)\ \times \frac{k_{mg}}{k_{g,corr}}\right)}{1000} \times 1.1 \qquad \text{Equation 4. 14}$$

Where:

22.9 and 39.3 is the energy content (MJ/kg) in protein and fat, respectively.

$gain_{prot} =$ daily protein retention (g/day). *See below.*

$gain_{fat} =$ daily fat retention (g/day). *See below.*

$k_{mg} =$ joint partial efficiency of ME for maintenance and growth. *See below.*

$k_{g,corr} =$ utilisation coefficient of ME to NE for growth. *See below.*

Daily protein retention, $gain_{prot}$ (g/day), is calculated as (Volden, 2011, eq 9.8):

$$gain_{prot} = factor_1 \times 1.06\ \times \left(EBWG - gain_{fat}\right) \times FFM^{0.06} \qquad \text{Equation 4. 15}$$

Where:

EBWG = Empty body weight gain (g/day). Calculated as:

$$EBWG = \frac{EBW}{BW}\ \times factor_6 \times DG_{calc} \times 1000 \qquad \text{Equation 4. 16}$$

Where:

$EBW =$ empty body weight, kg, *see Equation 4. 18.*

Factor_6 = coefficient that is dependent on breed and sex, Appendix table EE.

$DG_{calc} =$ daily weight gain, kg/day.

$FFM =$ Fat free mass (kg), calculated as:

$$FFM = EBW - Fat_{mass} \qquad \text{Equation 4. 17}$$

Where:

EBW = empty body weight, kg. Calculated as:

$$EBW = e^{(factor_7 + factor_6 \times \ln(BW))}$$ Equation 4. 18

Where:

$factor_7, factor_6 =$ coefficients dependent on breed and sex, Appendix table E

$BW =$ current body weight (kg).

$Fat_{mass} =$ Fat content in the EBW (kg), calculated as:

$$Fat_{mass} = e^{factor_2 + factor_3 \times \ln(EBW) + factor_4 \times \ln(EBW)^2))}$$ Equation 4. 19

Where:

$factor_2, factor_3, factor_4 =$ coefficients dependent on breed and sex, Appendix table EE.

Daily fat retention (g/day), $gain_{fat}$is calculated as (Volden, 2011, eq 9.9) and (Norfor, 2022):

$$Gain_{fat} = \left(\left(1000 \times \frac{Fat_{mass}}{EBW}\right) \times \left((factor_3 + 2 \times factor_4 \times \ln(EBW)) \times \frac{factor_5}{factor_5^{1.78}}\right)\right) \times \left(\frac{EBWG}{1000}\right)^{1.78}$$

Equation 4. 20

Where:

$factor_3, factor_4, factor_5 =$ coefficients dependent on breed and sex, Appendix table EE.

Appendix table E. Coefficients used for calculation fat and protein retention in growing cattle (Volden, 2011).

Animal	***$factor_1$***	***$factor_2$***	***$factor_3$***	***$factor_4$***	***$factor_5$***	***$factor_6$***	***$factor_7$***
Heifer or steer	0.1616	-6.311	1.811	0	0.8	1.046	-0.3939
Bull, early maturing	0.1541	-1.68	0.0189	0.1609	1	1.023	-0.2855
Bull, late maturing	0.1541	-5.433	1.5352	0	1.2	1.024	-0.2704
Bull, cross breed	0.1541	-5.7541	1.3708	0.0442	1	1.023	0.27795

Joint partial efficiency of ME for maintenance and growth, k_{mg}, calculated as (Volden, 2011, eq 8.5):

$$k_{mg} = k_m \times k_g \times \frac{APL}{\left(k_g + k_m \times (APL - 1)\right)}$$ Equation 4. 21

Where:

$k_m =$ the partial efficiency of ME for maintenance, calculated as:

$$k_m = 0.287 \times \frac{ME}{GE} + 0.554$$ Equation 4. 22

Where:

$ME =$ metabolizable energy

$GE =$ gross energy

There are unique functions to estimate ME and GE based on the feed characteristics and dry matter intake (DMI) of each feedstuff. However, DMI is most likely unknown, and DMI is to be calculated based on energy requirements for weight gain (including k_m).

It is assumed that the $\frac{ME}{GE}$ ratio is 0.60 for any feed ration. This is a common ratio applicable for feed rations (Åkerlind pers comm, 2021). Individual feeds and ingredients have higher or lower ME content. Some concentrates, protein feeds, cereals, etc. have higher ME content (up to circa 90% of GE), forage ca 55-62% ME of GE, and straw and bran the lowest (<50%).

Hence,

$k_m = 0.287 \ \times 0.6 + \ 0.554 = 0.7262.$

The partial efficiency of ME for growth, k_g is calculated as:

$$k_g = 0.78 \ \times \frac{ME}{GE} + \ 0.006$$ Equation 4. 23

Where:

$ME =$ Metabolizable energy

$GE =$ Gross energy

If the same assumptions are made as above, $k_g = 0.78 \ \times 0.6 + 0.006 = 0.474$

Animal production level, APL, calculated as (Volden, 2011, eq 8.4):

$$APL = \frac{\left(\left(BW^{0.75} \times k_m * APL_{factor_1} \times \frac{120}{88}\right) + \left(5.48 \ \times gain_{prot} + 9.39 \ \times gain_{fat}\right)\right)}{\left(BW^{0.75} \times k_m \times APL_{factor_1} \times \frac{120}{88}\right)}$$

Equation 4. 24

Where:

$APL_{factor_1}=$

- Heifers and steers, any breed = 90
- Bulls of dairy breeds and crossbreeds = 91
- Bulls of beef breeds = 100

Utilisation coefficient of ME to NE for growth, $k_{g,corr}$ is calculated as (Volden, 2011, eq 9.6):

$$k_{g,corr} = k_{g,corr,1} + k_{g,corr,k} \times (1 - Eq)^2 \qquad \text{Equation 4. 25}$$

Where:

$k_{g,corr,1} =$ 0.35

$k_{g,corr,k} =$ 0.25

$Eq =$ Daily NE requirement for protein retention related to the total daily NE retention, calculated as:

$$Eq = \frac{Eq_{k,prot} \times gain_{prot}}{Eq_{k,prot} \times gain_{prot} + Eq_{k,fat} \times gain_{fat}} \qquad \text{Equation 4. 26}$$

Where:

$Eq_{k,prot=}$ 5.48

$Eq_{k,fat=}$ 9.39

Energy content of feeds

The **gross energy content** of feeds, *GE* (MJ GE per kg DM), is calculated as:

$$GE = \frac{24.1 \times CP + 36.6 \times CFat + 18.5 \times (OM - CP - CFat)}{1000} \qquad \text{Equation 4. 27}$$

Where:

$CFat =$ Crude fat, g/kg DM

$OM =$ Organic matter content, g/kg DM. If OM is unknown but ash content (g ash per kg DM) is known, then OM is calculated as:

$$OM = 1000 - ash$$

$CP =$ Crude protein, g/kg DM

If the **net energy content** of the feed, *NE* (MJ NE per kg DM), is unknown then *NE* is estimated as:

$$NE = 0.36 \times GE$$ Equation 4. 28

Where:

0.36 = Typical ratio between net energy and gross energy content of feeds (pers comm Åkerlind, 2021). The ratio $\frac{NE}{GE}$ is close to 0.36 for a wide range of feeds.

$GE =$ Gross energy content of feeds, MJ GE per kg DM

Dry matter intake, DMI

The dry matter intake is constituted of concentrates, forage, and of pasture intake during the grazing period.

Dairy and beef cows

Concentrates

Concentrates given to cows are distributed proportionally to the annual energy requirement of all lactating dairy cows, and proportionally to the energy requirements of all beef cows during the stable period.

The proportion of concentrate *i* in the feed ration, k_i (kg DM of concentrate *i* per MJ NE) is estimated as:

$$k_i = \frac{m_i \times DM_i}{\sum_{a,n} NEL_{a,n} * \xi_n}$$ Equation 4. 29

Where:

m_i= The amount of concentrate *i* given to lactating dairy cows and beef cows, respectively, expressed as kg concentrate per year and animal subcategory. Data is provided by the farmer.

$DM_i =$ Dry matter content of concentrate *i* (%). The dry matter content is retrieved from a feed database.

$NEL_{a,n}$= The net energy requirements of cow a (MJ NE per head and day, see Equation 4. 1), on day n. In the above formula, this is summarized for all cows a of the same animal subcategory (lactating dairy cow or beef cow), and all days n of the year.

ξ_n= Indicates whether the animal is given concentrates on day n. This variable is 1 when the animal is given concentrates, and 0 when the animal is not given concentrates. ξ_n is 1 for all days (January 1st to December 31st) for lactating dairy cows. For beef cows, ξ_n is 1 during the stable period and 0 during the grazing period. The farmer indicates the grazing period manually in Agrosfär, and the stable period is assumed to equal days outside the grazing period.

The dry matter intake of concentrate i by animal a on day $n, DMI_i^{(conc)}$ (kg DM per head and day) is estimated as:

$$DMI_i^{(conc)} = k_i \times NEL_{a,n} \times \xi_n$$ Equation 4. 30

Where:

$DMI_i^{(conc)}$ = The proportion of concentrate i in the feed ration (kg DM concentrate i per MJ NEL), see Equation 4. 29

$NEL_{a,n}$ = The net energy requirement of cow a (MJ NE per head and day, see Equation 4. 1), on day n.

ξ_n= Indicates whether the animal is given concentrates on day n. This variable is 1 when the animal is given concentrates, and 0 when the animal is not given concentrates. ξ_n is 1 for all days (January 1st to December 31st) for lactating dairy cows. For beef cows, ξ_n is 1 during the stable period and 0 during the grazing period. The farmer indicates the grazing period manually in Agrosfär, and the stable period is assumed to equal days outside the grazing period.

The total dry matter intake of all concentrates by animal a on day n, $DMI^{(conc)}$ (kg DM concentrates per head and day) is summarized as:

$$DMI^{(conc)} = \sum_i DMI_i^{(conc)}$$ Equation 4. 31

Where:

$DMI_i^{(conc)}$ = Dry matter intake of concentrate i by animal a on day n (kg DM per head and day), see Equation 4. 30.

The net energy supplied from concentrate i to animal a on day n, $NEL_{i,a,n}^{(Conc)}$ (MJ NE per head and day) is then estimated as:

$$NEL_{i,a,n}^{(Conc)} = DMI_i^{(conc)} \times NE_i$$ Equation 4. 32

Where:

$DMI_i^{(conc)}$ = Dry matter intake of concentrate i by animal a on day n (kg DM per head and day), see Equation 4. 30.

NE_i = Net energy content of concentrate i (MJ per kg DM). NE_i is provided by the farmer or retrieved from a database.

Pasture intake

The energy supply from pasture intake to animal a on day n, $NEL_{a,n}^{(Pasture)}$ (MJ NE per cow and day during the grazing period) is estimated as:

$$NEL_{a,n}^{(Pasture)} = NEL_{a,n} \times \left(\frac{t_n}{24}\right)$$ Equation 4. 33

Where:

$NEL_{a,n}$ = The total net energy requirement of cow a (MJ NE per head and day, see Equation 4. 1), on day n.

t_n = Time spent outdoors grazing (in hours per day). During the grazing period, t_n is between 0 and 24. The farmer provides t_n manually in Agrofär for dairy cows. Beef cows are assumed to graze 24 hours per day during the grazing period.

t_n is always 0 outside the grazing period, which implies that $NEL_{a,n}^{(Pasture)}$ is always 0 outside the grazing period.

Lactating dairy cows: Note that the pasture intake is limited if the energy supplied from concentrates exceeds the energy content of feedstuffs supplied indoors during the grazing period, i.e. if concentrates constitute a very large share of the feed ration and/or the cows graze for many hours per day. Hence, if:

$$\sum_i NEL_{i,a,n}^{(Conc)} > \left(1 - \left(\frac{t_n}{24}\right)\right) \times NEL_{a,n}$$

Then:

$$NEL_{a,n}^{(Pasture)} = NEL_{a,n} - \sum_i NEL_{i,a,n}^{(Conc)}$$

Where:

$\sum_i NEL_{i,a,n}^{(Conc)}$ = The sum of net energy supplied from all concentrates i given to animal a (MJ NE per head and day), see Equation 4. 32. Note that the assumption is that dry dairy cows and beef cows are not fed concentrates during the grazing period. Hence, $\sum Conc_{i,NEL}$= 0 for dry dairy cows and beef cows during the grazing period.

The dry matter intake of pasture intake by animal a on day n, $DMI_{a,n}^{(Pasture)}$ (kg DM per head and day), during the grazing period is estimated as:

$$DMI_{a,n}^{(Pasture)} = \frac{NEL_{a,n}^{(Pasture)}}{NE^{(Pasture)}} \qquad \text{Equation 4. 34}$$

Where:

$NEL_{a,n}^{(Pasture)}$ =	The energy supply from pasture intake to animal a on day n (MJ NE per cow and day during the grazing period). See Equation 4. 33
$NE^{(Pasture)}$ =	Average net energy content of pasture intake (MJ per kg DM). In the current version of Agrosfär, $NE^{(Pasture)}$ is assumed to equal the average net energy content of forage given to the animal subcategory. The farmer provides information about the net energy content of any forage given to the animals (default values or farm-specific values) and the ratio of each forage given to each animal subcategory. See Equation 4. 37.

Forage

The amount of forage consumed by animal a on day n is estimated as the difference between the calculated energy requirement and the energy supplied from concentrates and pasture intake. The energy supply from forage, $NEL_{a,n}^{(Forage)}$ (MJ NE per cow and day) is then estimated as:

$$NEL_{a,n}^{(Forage)} = NEL_{a,n} - \sum_i NEL_{i,a,n}^{(Conc)} - NEL_{a,n}^{(Pasture)} \qquad \text{Equation 4. 35}$$

Where:

$NEL_{a,n}$ =	The total net energy requirement of cow a (MJ NE per head and day, see Equation 4. 1), on day n.
$\sum_i NEL_{i,a,n}^{(Conc)}$=	The sum of net energy supplied from all concentrates i given to animal a (MJ NE per head and day), see Equation 4. 32.
$NEL_{a,n}^{(Pasture)}$	The energy supply from pasture intake to animal a on day n (MJ NE per cow and day during the grazing period). See Equation 4. 33

The dry matter intake of forage by animal a on day n, $DMI_{a,n}^{(Forage)}$(kg DM per head and day) is estimated as:

$$DMI_{a,n}^{(Forage)} = \frac{NEL_{a,n}^{(Forage)}}{NE^{(Forage)}}$$

Equation 4. 36

Where:

$NEL_{a,n}^{(Forage)} =$	The energy supply from forage to animal a on day n (MJ NE per cow and day). See Equation 4. 35
$NE^{(Forage)} =$	The average net energy content of all forage given to the animal subcategory (MJ NE per kg DM). $NE^{(Forage)}$ is estimated as:

$$NE^{(Forage)} = \sum_{i} \left(NE_{i}^{(Forage)} \times \rho_i \right)$$

Equation 4. 37

Where:

$NE_{i}^{(Forage)} =$	Net energy content of forage i (MJ NE per kg DM). The farmer provides information about the net energy content of any forage given to the animals (default values or farm-specific values).
$\rho_i =$	The fraction of forage i in the forage feed ration. The farmer provides information on the ratio (0-100%) of each forage given to every animal subcategory. It should be noted that the total ratio for all forages i, sum to 100%, i.e. $\sum_i \rho_i = 1$.

Growing cattle, after weaning

The following section describes how the DMI of growing cattle after weaning is estimated. The weaning age is assumed to be 2 months for calves of dairy breeds and 3 months for calves of beef breeds.

Concentrates

Concentrates given to heifers, steers and bulls are distributed proportionally to the energy requirements post weaning of all animals in the animal subcategory. Concentrates are given to the animals during the stable period.

The proportion of concentrate *i* in the feed ration, *k_i* (kg DM of concentrate *i* per MJ NE) is estimated as:

$$k_i = \frac{m_i \times DM_i}{\sum_{a,n}(NEG_{a,n} \times \xi_n)}$$

Equation 4. 38

Where:

m_i= The amount of concentrate i given to heifers, steers and bulls, respectively, expressed as kg concentrate per year and animal subcategory. Data is provided by the farmer.

DM_i = Dry matter content of concentrate i (%). The dry matter content is retrieved from a feed database.

$NEG_{a,n}$= The net energy requirements of growing cattle a (MJ NE per head and day, see Equation 4. 12), on day n. In the above formula, this is summarized for all growing cattle a of the same animal subcategory (heifers, steers and bulls), and all days n of the year.

ξ_n= Indicates whether the animal is given concentrates on day n. This variable is 1 when the animal is given concentrates, and 0 when the animal is not given concentrates. ξ_n is 1 during the stable period and 0 during the grazing period. The farmer indicates the grazing period manually in Agrosfär, and the stable period is assumed to equal days outside the grazing period.

The dry matter intake of concentrate i by animal a on day $n, m_{i,a,n}$ (kg DM per head and day) is estimated as:

$$DMI_i^{(conc)} = k_i \times NEG_{a,n} \times \xi_n \qquad \text{Equation 4. 39}$$

Where:

$DMI_i^{(conc)}$ = The proportion of concentrate i in the feed ration (kg DM concentrate i per MJ NEL), see Equation 4. 39.

$NEG_{a,n}$ = The net energy requirement of growing cattle a (MJ NE per head and day, see Equation 4. 1), on day n.

ξ_n= Indicates whether the animal is given concentrates on day n. This variable is 1 when the animal is given concentrates, and 0 when the animal is not given concentrates. ξ_n is 1 during the stable period and 0 during the grazing period. The farmer indicates the grazing period manually in Agrosfär, and the stable period is assumed to equal days outside the grazing period.

The total dry matter intake of all concentrates by animal a on day n, $m_{a,n}$ (kg DM concentrates per head and day) is summarized as:

$$DMI^{(conc)} = \sum_i DMI_i^{(conc)}$$ Equation 4. 40

Where:

$DMI_i^{(conc)}$ = Dry matter intake of concentrate i by animal a on day n (kg DM per head and day), see Equation 4. 39.

The net energy supplied from concentrate i to animal a on day n, $NEG_{i,a,n}^{(Conc)}$ (MJ NE per growing cattle and day) is then estimated as:

$$NEG_{i,a,n}^{(Conc)} = DMI_i^{(conc)} \times NE_i$$ Equation 4. 41

Where:

$DMI_i^{(conc)}$ = Dry matter intake of concentrate i by animal a on day n (kg DM per head and day), see Equation 4. 40.

NE_i = Net energy content of concentrate i (MJ per kg DM). NE_i is provided by the farmer or retrieved from a database.

Pasture intake

Growing cattle are assumed to graze 24 hours per day during the grazing period. Pasture intake is thus assumed to cover the energy requirement of growing cattle during the grazing period. Hence, the energy supply from pasture intake to animal a on day n, $NEG_{a,n}^{(Pasture)}$ (MJ NE per growing cattle and day during the grazing period) is assumed to equal the net energy requirement of growing cattle:

$$NEG_{a,n}^{(Pasture)} = NEG_{a,n}$$ Equation 4. 42

Where:

$NEG_{a,n}$ = The total net energy requirement of growing cattle a (MJ NE per head and day, see Equation 4. 12), on day n during the grazing period.

The DMI of pasture intake by animal a on day n, $DMI_{a,n}^{(Pasture)}$ (kg DM per head and day), during the grazing period is estimated as:

$$DMI_{a,n}^{(Pasture)} = \frac{NEG_{a,n}^{(Pasture)}}{NE^{(Pasture)}}$$ Equation 4. 43

Where:

$NEG_{a,n}^{(Pasture)}$ = The energy supply from pasture intake to animal a on day n (MJ NE per cow and day during the grazing period). See Equation 4. 42.

$NE^{(Pasture)}$ = Average net energy content of pasture intake (MJ per kg DM). In the current version of Agrosfär, $NE^{(Pasture)}$ is assumed to equal the average net energy content of forage given to the animal subcategory. The farmer provides information about the net energy content of any forage given to the animals (default values or farm-specific values) and the ratio of each forage given to each animal subcategory. See Equation 4. 46.

Forage

Forage is given to growing cattle during the stable period. The amount of forage consumed by animal a on day n during the stable period is estimated as the difference between the calculated energy requirement and the energy supplied from concentrates. The energy supply from forage, $NEG_{a,n}^{(Forage)}$(MJ NE per growing cattle and day) is then estimated as:

$$NEG_{a,n}^{(Forage)} = NEG_{a,n} - \sum_{i} NEG_{i,a,n}^{(Conc)}$$

Equation 4. 44

Where:

$NEG_{a,n}$ = The total net energy requirement of growing cattle a (MJ NE per head and day, see Equation 4. 12), on day n during the stable period

$\sum_i NEG_{i,a,n}^{(Conc)}$= The sum of net energy supplied from all concentrates i given to animal a (MJ NE per head and day), see Equation 4. 41.

The dry matter intake of forage by animal a on day n during the stable period, $DMI_{a,n}^{(Forage)}$(kg DM per head and day) is estimated as:

$$DMI_{a,n}^{(Forage)} = \frac{NEG_{a,n}^{(Forage)}}{NE^{(Forage)}}$$

Equation 4. 45

Where:

$NEL_{a,n}^{(Forage)}$ = The energy supply from forage to animal a on day n (MJ NE per cow and day). See Equation 4. 44.

$NE^{(Forage)} =$ The average net energy content of all forage given to the animal subcategory (MJ NE per kg DM). $NE^{(Forage)}$ is estimated as:

$$NE^{(Forage)} = \sum_i \left(NE_i^{(Forage)} \times \rho_i \right) \qquad \text{Equation 4. 46}$$

Where:

$NE_i^{(Forage)} =$ Net energy content of forage i (MJ NE per kg DM). The farmer provides information about the net energy content of any forage given to the animals (default values or farm-specific values).

$\rho_i =$ The fraction of forage i in the forage feed ration. The farmer provides information on the ratio (0-100%) of each forage given to every animal subcategory. It should be noted that the total ratio for all forages i, sum to 100%, i.e., $\sum_i \rho_i = 1$.

Total feed intake – cows and growing cattle

The total dry matter intake of cows and growing cattle after weaning, *DMI* (kg DM per head and day), is summarized as:

$$DMI = DMI^{(Conc)} + DMI^{(Pasture)} + DMI^{(Forage)} \qquad \text{Equation 4. 47}$$

Where:

$DMI^{(Conc)} =$ DMI of concentrates (kg DM per head and day), see Equation 4. 31 (cows) and Equation 4. 41 (growing cattle).

$DMI^{(Pasture)} =$ DMI of pasture intake (kg DM per head and day), during the grazing period, see Equation 4. 34 (cows) and Equation 4. 43 (growing cattle).

$DMI^{(Forage)} =$ DMI of forage (kg DM per head and day), se Equation 4. 36 (cows) and Equation 4. 45 (growing cattle).

The total gross energy intake, *GEI* (MJ GE per head and day), is summarized for all feeds (i) and is estimated in a similar way:

$$GEI = \sum_i \left(DMI_i^{(Conc)} \times GE_i^{(Conc)} \right) + DMI_i^{(Pasture)} \times \sum_i \left(\sigma_i \times GE_i^{(Pasture)} \right) + DMI_i^{(Forage)} \times \sum_i \left(\rho_i \times GE_i^{(Forage)} \right)$$

Equation 4. 48

Where:

$DMI_i^{(Conc)}$ = The dry matter intake of concentrate (i) (kg DM per head and day).

$GE_i^{(Conc)}$ = The gross energy content of concentrate (i) (MJ GE per kg DM). The gross energy content is estimated as in Equation 4. 27

$DMI_i^{(Pasture)}$ = The dry matter intake of pasture intake (kg DM per head and day) during the grazing period

σ_i = The proportion of pasture (i) of the pasture intake. In the current version of Agrosfär, σ_i is assume to equal ρ_i

$GE_i^{(Pasture)}$ = The gross energy content of pasture intake (i) (MJ GE per kg DM). In the current version of Agrosfär, $Pasture_{i,GE}$ is assume to equal $Forage_{i,GE}$

$DMI_i^{(Forage)}$ = The dry matter intake of forage (kg DM per head and day).

ρ_i = The proportion of forage (i) in the forage feed ration. The farmer provides information on the ratio (0-100%) of each forage given to every animal subcategory.

$GE_i^{(Forage)}$ = The gross energy content of forage (i) (MJ GE per kg DM). The gross energy content is estimated as in Equation 4. 27

In addition, the average nutrient content of the feed ration is needed in some equations. This includes crude protein (Cp_{feed} (g per kg DM)), crude fat ($CFat_{feed}$ (g per kg DM)), fatty acids (FA_{feed} (g per kg crude fat, *CFat*)) and ash (Ash_{feed} (g per kg DM)).

For example, the average crude protein content of for all feedstuff i in the feed ration, Cp_{feed} (g per kg DM), is estimated as:

$$Cp_{feed} = \frac{\sum_i (DMI_i \times Cp_i)}{DMI} \qquad \text{Equation 4. 49}$$

Where:

DMI_i = The dry mater intake of feed i (kg DM per head and day). This includes all concentrates, paste intake and forage given to the animal, respectively.

Cp_i = The crude protein content of feed i (g per kg DM). The crude protein content is provided by the farmer or retrieved from a feed database.

DMI = Dry matter intake (kg DM per head and day), see Equation 4. 47.

The average content of crude fat, fatty acids and ash in the feed ration is estimated in a similar way. The only difference is that the content of these components in feedstuffs is retrieved from a feed database.

Enteric fermentation

Methane emissions from enteric fermentation, EF^{CH4} (kg CH_4 per head and day) is estimated as:

$$EF^{CH4} = \frac{EF_{MJ}^{CH4}}{55.65} \qquad \text{Equation 4. 50}$$

Where:

EF_{MJ}^{CH4}= Methane emission from enteric fermentation (MJ CH_4 per head and day), see Equation 4. 51 (cows) and Equation 4. 53 (growing cattle).

55.65 = Energy content of methane (MJ CH_4 per kg CH_4)

Methane from enteric fermentations in cows (not including growing cattle), $EF_{MJ,cow}^{CH4}$ (MJ CH_4 per cow and day) is estimated as:

$$EF_{MJ,cow}^{CH4} = 1.39 \times DMI - 0.091 \times FA_{Feed} \times \frac{CFat_{feed}}{1000} \qquad \text{Equation 4. 51}$$

Where:

DMI = Dry matter intake, kg DM per head and day, Equation 4. 47

FA_{Feed} = Fatty acid concentration in the feed ration (g FA per kg CFat).

$CFat_{feed}$ = Concentration of Crude fat in the feed ration (g CFat per kg DM).

FA_{Feed} and $CFat_{feed}$ is estimated similarly to Cp_{feed} as described in Equation 4. 49.

Fatty acids are reported in the Norfor table for many feedstuffs, but fatty acids are not included in all feed analyses and databases. However, fatty acid content of feedstuffs can be estimated as 650 g FA per kg CFat in forage and 750 g FA per kg CFat in concentrates (Volden, 2011).

Hence, if FA_{Feed} is unknown, FA_{Feed} (g FA per kg Cfat) can be estimated as:

$$FA_{Feed} = 650 \times \left(1 - DMI^{(conc)}\right) + 750 \times DMI^{(conc)} \qquad \text{Equation 4. 52}$$

Where:

$DMI^{(conc)} =$ DMI of concentrates (kg DM concentrates per head and day), see Equation 4. 31.

$DMI =$ Dry matter intake, kg DM per head and day, Equation 4. 47.

Methane from enteric fermentations in growing cattle (not including cows), $EF_{MJ,growing}^{CH4}$ (MJ CH_4 per growing cattle and day) is estimated (based on Bertilsson, 2016) as:

$$EF_{MJ,growing}^{CH4} = \left(\frac{-0.046 \times DMI^{(conc)}}{DMI} + 0.071379 \right) \times GEI \qquad \text{Equation 4. 53}$$

Where:

$DMI^{(conc)} =$ DMI of concentrates (kg DM concentrates per head and day), see Equation 4. 40

$DMI =$ Dry matter intake, kg DM per head and day, Equation 4. 47

$GEI =$ Gross energy intake, (MJ GE per head and day), see Equation 4. 48.

Note that the equation is somewhat modified compared to Bertilsson (2016). Bertilsson expresses the emissions from growing cattle as % of gross energy intake (MJ GE). Here, the parameter *GEI* is added to express the emissions as MJ CH_4 per head and day.

In addition, the proportion of concentrates $\left(\frac{DMI^{(conc)}}{DMI}\right)$ is expressed differently. In Bertilsson, the proportion is expressed as a number between 0-100 $\left(0 < \frac{DMI^{(conc)}}{DMI} < 100\right)$. Here it is expressed as a share $\left(0 < \frac{DMI^{(conc)}}{DMI} < 1.00\right)$. The equation is modified consistently. Hence, the intercept is "0.071379" instead of 7.1379, as in Bertilsson (2016).

Manure management

Methane emissions

Methane emissions from manure management, MM^{CH4} (kg CH_4 per head and day), is summarized for all manure from animal a in every manure management system j on day n, and is estimated (based on Gavrilova et al., 2019) as:

$$MM^{CH4} = 0.67 \times VS \times \left(B_0^p \times MCF^p \times \frac{t_n}{24} + B_o \times \sum_j \left[\tau_j^{VS} \times MCF_j \times \left(1 - \frac{t_n}{24}\right)\right]\right)$$

Equation 4. 54

Where:

$0.67 =$ Conversion factor from m³ CH_4 to kg CH_4

$VS =$ Excretion rate of volatile solids, VS (kg VS per head and day), see Equation 4. 55 below.

$B_0^p =$ The maximum methane producing capacity of the manure dropped on pasture (m³ CH_4 per kg VS). B_0^p = 0.19 m³ CH_4 per kg VS for all cattle manure dropped on pasture (Gavrilova et al., 2019).

$MCF^p =$ Methane Conversion Factor, % of B_0, for manure dropped on pasture, see Appendix table .

$t_n =$ Time spent outdoors grazing during day n (hours per day). $t_n = 0$ during the stable period for all cattle. During the grazing period, t_n = 24 for all cattle but dairy cows, and $0 \leq t_n \leq 24$ for dairy cows.

$B_0 =$ The maximum methane producing capacity of manure (m³ CH_4 per kg VS). In the current version of Agrosfär, $B_0 = 0.24$ m³ CH_4 per kg VS for dairy cows, and 0.18 m³ CH_4 per kg VS for other cattle, which corresponds to the IPCC default values for cattle in Western Europe (Gavrilova et al., 2019).

More specific B_0values, for example those estimated based on DMI and feeding strategy, are preferred but are not yet available.

Note the difference between B_0 and B_0^p. MCF^p must always be used in conjunction with a B_0^p value of 0.19 m³ CH_4 per kg VS.

$\tau_j^{VS} =$ Fraction (%) of the VS in manure stored in manure management system j dependent on housing system. The farmer indicates manually the distribution between housing systems (number of heads per system). The manure is distributed proportionally between housing system. Every housing system generates one or more types of manure. If the housing system generates more than one type of manure, e.g. deep bedding and slurry, then the VS is distributed further between manure management systems dependent on the housing system.

$\left(1 - \frac{t_n}{24}\right) =$ Describes the time spent indoors during day n (% of the day). $\left(1 - \frac{t_n}{24}\right) = 1$ during the stable period for all cattle. During the grazing period, $\left(1 - \frac{t_n}{24}\right)$ = 0 for all cattle but dairy cows, and $0 \leq \left(1 - \frac{t_n}{24}\right) \leq 1$ for dairy cows.

$MCF_j =$ Methane Conversion Factor, % of B_0, of manure dropped indoors and that ends up in management system j, see Appendix table F. MCF comes from the Swedish national inventory of GHG emissions, NIR

(Naturvårdsverket, 2021b). Sweden has implemented a national MCF for slurry, whereas the MCF for other types of manure is based on the IPCC guidelines. MCF is dependent on the type of manure stored, but NIR doesn't differentiate between storage techniques.

The IPCC guidelines includes methane conversion factors dependent on storage and coverage techniques, for example, slurry stored with or without natural crust, but the MCFs presented in NIR are deemed more appropriate for Agrosfär since they represent Swedish conditions.

Appendix table F. Emission factors applied to estimate emissions of CH_4 (MCF, % of B_0) and direct N_2O (EF_3, kg N_2O-N per kg N excreted) from the storage of manure (Naturvårdsverket, 2021a).

Manure management system, and covering of the manure storage	MCF	EF_3
Deep bedding	17%	1%
Slurry, with natural crust	3.5%	0.5%
Slurry, with other cover	3.5%	0.5%
Slurry, without cover	3.5%	0.5%
Solid manure	2%	0.5%
Urine stored with slurry[1]	3.5%	0.5%
Urine with cover[1]	3.5%	0.5%
Urine, without cover[1]	3.5%	0.5%
Pasture	1%	2%

[1] Urine: MCF and EF_3 is assumed to be the same as for Slurry.

VS excretion rate, *VS* (kg VS per head and day), is estimated based on the Norfor method. *VS* excreted is denoted OM_faeces in Norfor (Norfor 2022, eq. 12.28). VS excreted by animal a on day n is calculated as:

$$VS = \sum \frac{DMI_i \times (1000 - Ash_i - td_{OM_i})}{1000} \qquad \text{Equation 4. 55}$$

Where:

$DMI_i =$ Dry matter intake by of feed i of animal a on day n (kg DM per head and day), see Equation 4. 31 to Equation 4. 45.

$Ash_i =$ Ash content of feed i (g ash per kg DM). Ash_i is provided from feed tables.

$td_{OM_i} =$ Total apparently digested organic matter of feed i (g per kg DM). In the current version of Agrosfär, the feed database contains td_{OM_i} for all feedstuffs available in Agrosfär.

100% of VS is excreted as faeces, 0% as urine.

Direct nitrous oxide emission

Direct N_2O emissions, MM^{dN_2O} (kg N_2O per head and day), from all manure from animal a in every manure management systems j on day n, is estimated (based on Gavrilova et al., 2019) as:

$$MM^{dN_2O} = \frac{44}{28} \times N_{ex} \times \left(EF_3^p \times \frac{t_n}{24} + \sum_j \left[\tau_j^N \times EF_{3_i} \left(1 - \frac{t_n}{24}\right)\right]\right) \qquad \text{Equation 4. 56}$$

Where:

$\frac{44}{28} =$ Conversion of N_2O-N to N_2O emissions (kg N_2O per kg N_2O-N).

$N_{ex} =$ N excretion rate (kg N per head and day), see Equation 4. 57. Note that the IPCC guideline express the amount of N as N excreted, regardless of prior losses of N, e.g. ammonia emissions in the stable.

$EF_3^p =$ Emission factor for direct N_2O-N from manure dropped on pasture (kg N_2O-N per kg N excreted), see Appendix table F.

$t_n =$ Time spent outdoors grazing during day n (hours per day). $t_n = 0$ during the stable period for all cattle. During the grazing period, $t_n = 24$ for all cattle but dairy cows, and $0 \leq t_n \leq 24$ for dairy cows.

$\tau_j^N =$ Fraction (%) of the N in manure stored in manure management system j dependent on housing system i. The farmer indicates manually the distribution between housing systems (number of heads per system). The distribution of N between housing systems and eventually manure management systems is similar to τ_j^{VS} as in Equation 4. 54. However, τ_j^N does not have to equal τ_j^{VS} for a given housing system i since the fate of urine and faeces may differ and all VS comes from faeces, whereas N is distributed between urine and faeces.

$EF_{3_j} =$ Emission factor for direct N_2O-N from manure dropped indoors and that ends up in manure management system j (kg N_2O-N per kg N excreted), see Appendix table F.

$\left(1 - \frac{t_n}{24}\right) =$ Describes the time spent indoors during day n (% of the day). $\left(1 - \frac{t_n}{24}\right) = 1$ during the stable period for all cattle. During the grazing period, $\left(1 - \frac{t_n}{24}\right) = 0$ for all cattle but dairy cows, and $0 \leq \left(1 - \frac{t_n}{24}\right) \leq 1$ for dairy cows.

N excretion rate, N_{ex} (kg N per head and day), of animal a on day n is estimate as (Volden, 2011):

$$N_{ex} = \frac{DMI \times Cp_{feed} \times 0.16 - N_u}{1000}$$ Equation 4. 57

Where:

$DMI =$ Dry matter intake of animal a on day n (kg DM per head and day).

$Cp_{feed} =$ Average crude protein content in the feed ration of animal a on day n (g Cp per kg DM). See Equation 4. 49.

$0.16 =$ Conversion of crude protein to N (kg N per kg Cp)

$N_u =$ Total amount of utilised N of animal a on day n (g N per head and day). N_u is estimated as:

$$N_u = N_{milk} + N_{gest} + N_{gain}$$ Equation 4. 58

Where:

N_{milk}, N_{gest} and N_{gain} are the amount of N incorporated in milk, foetus and weight gain, respectively (g N per head and day), of animal a on day n, see below.

N_{milk} (g N per head and day) is estimated as:

$$N_{milk} = yield_{milk} \times p_{milk} \times 0.15674$$ Equation 4. 59

Where:

$yield_{milk} =$ Milk yield (kg milk per head and day)

$p_{milk} =$ Protein content of the milk (g protein per kg milk). *Note the unit. Protein content can be expressed as percent.*

$0.15674 =$ N content in milk protein (kg N per kg p_{milk})

N_{gest} (g N per head and day) is estimated as:

$$N_{gest} = 0.16 \times 0.5 \times AAT_{N_{gest}}$$ Equation 4. 60

Where:

$0.16 =$ N proportion in protein (kg N per kg protein)

$0.5 =$ The utilisation factor for amino acids

$AAT_{N_{gest}}=$ Amino acid requirement for gestation (g amino acids per head and day). $AAT_{N_{gest}}$ is estimated as:

$$AAT_{N_{gest}} = \frac{\frac{BW_{mat}}{600} \times 34.375 \times e^{8.5357-\left(13.1201\times e^{-0.00262\times gest_{day}}\right)} - 0.00262 \times gest_{day}}{0.5}$$

Equation 4. 61

Where:

$BW_{mat} =$ Mature body weight (kg). Default values per breed as given in Norfor (2022).

$gest_{day} =$ Day in gestation (day). See Equation 4. 3.

$0.5 =$ The assumed AAT_N (amino acids absorbed in small intestine) utilization for gestation.

N_{gain} (g N per head and day) is estimated as:

$$N_{gain} = gain_{prot} \times 0.16$$

Equation 4. 62

Where:

$0.16 =$ N proportion in protein (kg N per kg protein)

$gain_{prot} =$ Daily protein gain (g protein per day). See Equation 4. 15.

Note: $gain_{prot}$ refers to weight gain in growing cattle (heifers, bulls and steers). There are no clear suggestions in the documentation of the Norfor system on how to address N_{gain} of young cows (1st and 2nd lactation). However, growth of young cows is considered when protein requirements (AAT_N, amino acids absorbed in small intestine) of cows are estimated. AAT_N requirements for growth in cows (1st and 2nd lactation) is based on the requirements of growing heifers.

Assumption: Daily protein gain for growing cows (i.e. 1st and 2nd lactation) is estimated similar to protein gain in heifers.

Note that this assumption is not relevant for estimations of energy requirement of growing cows since there are separate equations for young cows (NEL_{gain}, see Equation 4. 4) and heifers (NEG_{gain}, see Equation 4. 14 – Equation 4. 26).

Indirect nitrous oxide emissions

Indirect N_2O emissions, MM^{iN_2O} (kg N_2O per head and day), from all manure from animal a in housing system i, storage systems j and pasture on day n, is estimated (based on Gavrilova et al., 2019) as:

$$MM^{iN_2O} = \frac{44}{28} \times EF_4 \times \left(\sum_i N_{vol_i}^{stable} + \sum_{i,j,k} N_{vol_{i,j,k}}^{storage} + N_{vol}^{pasture} \right)$$ Equation 4. 63

Where:

$\frac{44}{28} =$ Conversion of N_2O-N to N_2O emissions (kg N_2O per kg N_2O-N)

$EF_4 =$ Emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, (kg N_2O-N per kg NH_3-N volatilised). $EF_4 = 0.01$, which is the default aggregated value in the IPCC guidelines (Gavrilova et al., 2019).

$N_{vol_i}^{stable} =$ The amount of N lost as ammonia in the stable per housing system i (kg NH_3-N per head and day), Equation 4. 64

$N_{vol_{i,j,k}}^{storage} =$ The amount of N lost as ammonia from storage system j containing manure from housing system i produced day n and with the storage option k ammonia from storage system j d (kg NH_3-N per head and day), see Equation 4. 67

$N_{vol}^{pasture} =$ The amount of N lost as ammonia from manure dropped on pasture (kg NH_3-N per head and day)

The amount of N lost as ammonia in the stable per housing system i, $N_{vol_i}^{stable}$ (kg NH_3-N per head and day), is estimated per day n as:

$$N_{vol_i}^{stable} = \tau_i \times \left(N_{ex} \times \left(1 - \frac{t_n}{24}\right) + N_{bedding_i} \times \zeta_n \right) \times FracGAS_{1_i}$$ Equation 4. 64

Where:

$\tau_i =$ Fraction (%) of manure dropped in housing system i during the stable period. The farmer indicates manually the distribution between housing systems (number of heads per system). The manure is assumed to be distributed proportionally. The sum of all τ_i should equal 100%, that is $\sum_i(\tau_i) = 1$.

$N_{ex} =$ N excretion rate (kg N per head and day) of animal a on day n, see Equation 4. 57

$\left(1 - \frac{t_n}{24}\right) =$ Describes the time spent indoors during day n (% of the day). $\left(1 - \frac{t_n}{24}\right) = 1$ during the stable period for all cattle. During the grazing period, $\left(1 - \frac{t_n}{24}\right) = 0$ for all cattle but dairy cows, and $0 \leq \left(1 - \frac{t_n}{24}\right) \leq 1$ for dairy cows.

$N_{bedding_i}$ = N in bedding materials (kg N per head and housing system i and day). $N_{bedding_i}$ is estimated as a function of kg bedding material used (default values per housing system i and (kg per day and per animal subcategory)) and the N content of bedding material. Straw is assumed to be used as bedding material. The N content of straw is assumed to be 0.7% N.

ζ_n = Indicates whether bedding materials are applied day n. This variable is 1 when bedding materials are applied in the stable, and 0 when no bedding materials are applied. It's assumed that ξ_n is 0 when the animals are outdoors 24 h per day ($t_n = 24$), and ξ_n is 1 when the animals are in the stable for part of the day or the entire day ($t_n \neq 24$).

$FracGAS_{1_i}$= Fraction of nitrogen that volatilises as NH_3 (kg NH_3-N per kg N) in the stable for housing system i. $FracGAS_{1_i}$ is derived from VERA and supporting materials.

The amount of N that remains in the manure after ammonia emissions in the stable is estimated separately for faeces and urine. 50% of N_{ex} is assumed to be excreted as faeces and 50% as urine. N in bedding materials ($N_{bedding}$) is assumed to end up in the same faction as faeces. $FracGAS_1$ is assumed to be the same for urine and faeces. Hence, the amount of N that remains after ammonia emissions in the stable from housing system i (kg N per head and day) is estimated as:

$$N_{urine_i} = 0.5 \times \tau_i \times N_{ex} \times \left(1 - \frac{t_n}{24}\right) \times \left(1 - FracGAS_{1_i}\right) \qquad \text{Equation 4. 65}$$

$$\begin{aligned} N_{faeces_i} = 0.5 \times \tau_i \times \left(N_{ex} \times \left(1 - \frac{t_n}{24}\right) + N_{bedding_i} \times \zeta_n\right) \\ \times \left(1 - FracGAS_{1_i}\right) \end{aligned} \qquad \text{Equation 4. 66}$$

Where:

N_{urine_i} = N content of urine from housing system i (kg N per head and day)

N_{faeces_i} = N content of faeces and bedding materials from housing system i (kg N per head and day)

0.5 = The fraction of N_{ex} that ends up in urine and faeces, respectively.

The remaining variables as above.

The manure produced in housing system i is automatically distributed between storage systems j. The farmer indicates the storage option(s) k for every storage system present on the farm, for example, covering technique.

The amount of N lost as ammonia from storage system j containing manure from housing system i produced day n and with the storage option k, $N_{vol_{i,j,k}}^{storage}$ (kg NH_3-N per head and day), is estimated as:

$$N_{vol_{i,j,k}}^{storage} = \left(N_{urine_i} \times u_{i,j,k} + N_{faeces_i} \times f_{i,j,k}\right) \times FracGAS_{2_{j,k}} \qquad \text{Equation 4. 67}$$

Where:

N_{urine_i} and N_{faeces_i} as above

$u_{i,j,k} =$	The fraction of urine from housing system i that ends up in storage system j with storage option k.
$f_{i,j,k} =$	The fraction of faeces and bedding materials from housing system i that ends up in storage system j with storage option k.
$FracGAS_{2_{j,k}} =$	Fraction of nitrogen that volatilises as NH_3 (kg NH_3-N per kg N) during the storage of manure from storage system j with storage option k. $FracGAS_{2_{j,k}}$ is derived from VERA and supporting materials.

The amount of N lost as ammonia from manure dropped on pasture, $N_{vol}^{pasture}$ (kg NH_3-N per head and day), is estimated as:

$$N_{vol}^{pasture} = N_{ex} \times \frac{t_n}{24} \times FracGAS_2^p \qquad \text{Equation 4. 68}$$

Where:

$N_{ex} =$	N excretion rate (kg N per head and day) of animal a on day n, see Equation 4. 57
$t_n =$	Time spent outdoors grazing during day n (hours per day). $t_n = 0$ during the stable period for all cattle. During the grazing period, $t_n = 24$ for all cattle but dairy cows, and $0 \leq t_n \leq 24$ for dairy cows.
$FracGAS_2^p =$	Fraction of nitrogen that volatilises as NH_3 (kg NH_3-N per kg N) from manure dropped on pasture. $FracGAS_2^p$ is assumed to be 20% based on VERA.

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Appendix 5: Energy use on farm-Equations

$$CItot_{energy} = \sum_{l} CFenergy_l \times EFfuel_l + \sum_{m} CEenergy_m \times EFel_m + \sum_{n} CEheat_n \times EFheat_n$$

Equation 5. 1

Where:

$CItot_{energy}$= Total climate impact used energy, [kg CO_2-eq.]

$CFdry$= Measured fuel consumption, [$unit$/y], unit may vary with fuel type

$EFfuel_l$= Emission factor of fuel type l, [kg CO_2-eq./$unit$], unit may vary with fuel type

$CEdry$= Measured electricity consumption, [MWh/y]

$EFel_m$= Emission factor of electricity source m, [kg CO_2-eq./MWh]

$CHenergy$= Measured heat consumption, [MWh/y]

$EFheat_n$= Emission factor of heat source n, [kg CO_2-eq./MWh]

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Review statement

Third-party review of The Agrosfär climate calculation model

The Agrosfär climate calculation model has gone through a third-party revision, performed by Andreas Asker and Martyna Mikusinska, LCA experts at Sweco. The revision has had two main purposes, namely;

1. Assessment of the quality assurance process in the development of Agrosfär.

2. Verification the completeness of previously conducted audits (Excel matrices) and review whether the requirements of three methodological standards issued by The Greenhouse Gas Protocol are met.

Sweco's assessment is that throughout the process of developing Agrosfär, there has been a consensus among the involved parties on what the goal of the tool is and that the working process has been directed to achieve this. In the development process the team has consulted external experts for key issues and reconsidered its own working methods when they have not fulfilled their purposes.

The performed review confirms that the Agrosfär climate calculation model, and the methodological foundation that it is based upon, has been developed with care and good insight and understanding of relevant and applicable LCA methodology and standards.

This gives a robust foundation for calculating credible results, although quality of the results also will be affected by the quality of the specific input data of the reporting farm.

Further, the verification according to *the Greenhouse Gas Protocol corporate standard*, *the Agricultural Guidance* and *the Scope 3 standard* has shown that previously done audits conducted by RISE has been complete in regard to covering all the standards requirements. As Agrosfär is a tool and not a reporting company, some of the requirements in the standards are not applicable to the tool or not possible to evaluate without also evaluating user data.

Swecos assessment is that the tool complies with the standards accounting principles, but that the standard's requirements on accounting cannot be fully met without also assessing the user data. No functionality is currently included in the Agrosfär tool that supports assessment of data quality, but it is part of Agrosfärs development plan.

The tool itself is no reporting company which many of the requirements are set to address. This means that certain requirements cannot be met directly, but future development of the Agrosfär tool can be developed to guide the user in this process. The development team of Agrosfär has already taken measures to address this issue and are currently investigating how to best support users in future development of the tool. This also applies for the reporting requirements (also applicable for the Agricultural Guidance and Scope 3 standard) where the tool does not currently support a report function to address all the requirements when the accounting result is to be presented publicly. Parts of the reporting requirements are met today but this information is only available in the Agrosfär methodological report and is thus not easily accessible for the user.

Requirements of the corporate standard for setting organizational and operational boundaries (chapter 3) are met in the corporate standard. Swecos assessment is that the Scope 3 standard "setting the Scope 3 boundary" is not fully met. More specifically, the justification of excluded upstream categories needs to be further elaborated.

More details and recommendations have been delivered in a review report.

Andreas Asker, Sweco Sverige AB,

2024-02-05

Martyna Mikusinska, Sweco Sverige AB,

2024-02-05