**Holos Version 4.0**

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**Algorithm Documentation**

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**Navigation of the document**

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**Open source linkages**

All table references are hyperlinked to tables located on our [GitHub repository](https://github.com/holos-aafc/Holos). This is both for the purpose of facilitating collaborations (they thus become living documents that can be updated over time) and for keeping this algorithm document valid for longer. In order to see the tables on GitHub, just follow the link. To request edits to one or more of the tables via Github, you must first create a GitHub account and then follow the instructions in this [user guide](https://github.com/holos-aafc/Holos/blob/main/H.Content/Documentation/User%20Guide/User%20Guide.md).

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| **Table 25** | Pregnancy coefficients for sheep | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_25_Pregnancy_Coefficients_For_Sheep_Provider.cs) | C# code |
| **Table 26** | Diet coefficients for sheep | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_18_26_Diet_Coefficients_For_Beef_Dairy_Sheep.csv) | CSV |
| **Table 27** | Enteric CH4 emission rates for swine, poultry and other livestock types | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_27_Enteric_CH4_Swine_Poultry_OtherLivestock_Provider.cs) | C# code |
| **Table 28** | Average number of production days per production cycle and the number of non-production days between cycles per year for “all in, all out” systems | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_28_Average_Number_Of_Production_Days.csv) | CSV |
| **Table 29** | Percentage of total manure produced managed in different manure management systems, by livestock type, in Canada, and daily manure excretion rates (*Manureexcretion\_rate*) for sheep, poultry and other livestock | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_29_Percentage_Total_Manure_Produced_In_Systems.csv) | CSV |
| **Table 30** | Default bedding application rates and composition of bedding materials for all livestock types | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_30_Default_Bedding_Material_Composition_Provider.cs) | C# code |
| **Table 31** | Volatile solid excretion for performance standard diets for each pig group, by province | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_31_Swine_VS_Excretion_For_Diets_Provider.cs) | C# code |
| **Table 32** | Volatile solid and nitrogen excretion adjustment factors for swine, by diet | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_32_Swine_VS_Nitrogen_Excretion_Factors_Provider.cs) | C# code |
| **Table 33** | Daily feed intake (as fed) for each swine group | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_33_Daily_Feed_Intake_For_Swine_Groups.csv) | CSV |
| **Table 34** | Daily volatile solid excretion factors for chickens, goats, llamas and alpacas, horses, mules and bison | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_34_Livestock_Daily_Volatile_Excretion_Factors_Provider.cs) | C# code |
| **Table 35** | Default values for maximum methane producing capacity (Bo) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_35_Methane_Producing_Capacity_Default_Values_Provider.cs) | C# code |
| **Table 36** | Default methane conversion factors, direct N2O emission factors, volatilization and leaching fractions and emission factors, by livestock type and manure handling system (for beef cattle, dairy cattle, broilers, layers and turkeys), the *Fracvolatilization* values are estimated within Holos, alternative IPCC (2019) defaults are provided in this table | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_36_Livestock_Emission_Conversion_Factors_Provider.cs) | C# code |
| **Table 37** | Methane conversion factors (MCF) by climate zone and manure handling system | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_37_MCF_By_Climate_Livestock_MansureSystem_Provider.cs) | C# code |
| **Table 38** | Default CH4 emission factors for solid manure for other livestock types | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_38_OtherLivestock_Default_CH4_Emission_Factors_Provider.cs) | C# code |
| **Table 39** | Crude protein content in feed, as fed, for each pig group, by province | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_39_Crude_Protein_Content_Swine_Feed_Provider.cs) | C# code |
| **Table 40** | Default values for *PRgain* by growth stage for growing pigs | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_40_Swine_Default_PrGain_Values_Provider.cs) | C# code |
| **Table 41** | Parameter values for pullets, broilers (incl. roasters) and layers for the estimation of *Nexcretion\_rate* | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_41_Poultry_N_Excretion_Rate_Parameter_Values.csv) | CSV |
| **Table 42** | Default nitrogen excretion rates for poultry and other livestock | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_42_Poultry_OtherLivestock_Default_NExcretionRates_Provider.cs) | C# code |
| **Table 43** | Default emission factors (kg NH3-N kg-1 TAN) for housing storage and land application of beef and dairy cattle manure at the reference temperature of 15 °C (Chai et al., 2014,2016) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_43_Beef_Dairy_Default_Emission_Factors_Provider.cs) | C# code |
| **Table 44** | Fraction of organic N mineralized as TAN and the fraction of TAN immobilized to organic N and nitrified and denitrified during solid and liquid manure storage for beef and dairy cattle (based on TAN content) (Chai et al., 2014,2016) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_44_Fraction_OrganicN_Mineralized_As_Tan_Provider.cs) | C# code |
| **Table 45** | Parameter adjustments for dried or stockpiled manure entering the anaerobic digester | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/AnaerobicDigestion/Table_45_Parameter_Adjustments_For_Manure_Provider.cs) | C# code |
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| **Table 51** | Herbicide energy requirement (*Eherbicide*) estimates for various crops in different regions of Canada for specific soils and tillage operations1 (GJ ha-1) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_51_Herbicide_Energy_Requirement_Estimates_By_Region.csv) | CSV |
| **Table 52** | Crop type table for Eastern Canada, used to determine *Efuel* and *Eherbicide* value | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Plants/Table_52_CropType_Table_For_Fuel_Herbicide_Values_Provider.cs) | C# code |
| **Table 53** | Crop prices | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Economic.Data/Data/Crops/Holos.Crops.csv) | CSV |
| **Table 54** | Global warming potential of emissions | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_54_Global_Warming_Potential_Of_Emissions.csv) | CSV |
| **Table 55** | Global radiative forcing (relative to 1750, in W m-2) (<https://www.esrl.noaa.gov/gmd/aggi/aggi.html>) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_55_Global_Radiative_Forcing.csv) | CSV |
| **Table 56** | Conversion factors from atomic weight to molecular weight | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_56_Conversion_Factors_Atomic_To_Molecular_Weight.csv) | CSV |
| **Table 57** | Relative uncertainties for each emission category | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Emissions/Table_57_58_Expression_Of_Uncertainty_Calculator.cs) | C# code |
| **Table 58** | Uncertainty categories and associated estimates | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Emissions/Table_57_58_Expression_Of_Uncertainty_Calculator.cs) | C# code |
| **Table 59** | Output for report | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_59_Output_For_Report.csv) | CSV |
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| **Table 61** | Fractions of dairy cattle N volatilized as ammonia resulting from the application of manure N fertilizer, from select years, 1990–2020, at a provincial scale | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_61_Fractions_of_dairy_cattle_N_volatilized.csv) | CSV |
| **Table 62** | Fractions of swine N volatilized as ammonia resulting from the application of manure N fertilizer, from select years, 1990–2020, at a provincial scale | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_62_Fractions_of_swine_N_volatilized.csv) | CSV |

# Introduction

## Purpose of the Holos model

The Holos model is a software application developed and provided by Agriculture and Agri-Food Canada (AAFC) to estimate greenhouse gas (GHG) emissions and soil C changes from Canadian farming systems. The development of the Holos model drives innovation and ingenuity for the benefit of all Canadians through the adoption of scientific research that develops new knowledge and technologies, transferring them to the agriculture and agri-food sector in the form of a software application. The model’s development focusses on enhancing the environmental sustainability of Canadian farming systems (while attempting to capture market opportunities) by testing, validating, and providing sustainabilty attributes for Canadian agricultural production systems.

The development of the Holos model aligns with AAFC’s agro-ecosystem resilience strategy, which aims to reduce the environmental footprint of agricultural production, and thus also interlinks closely with other AAFC sector strategies. For this purpose, the model combines country-specific emission factors and algorithms in a whole-farm approach that encompasses all components of a farm system, which can include different common livestock types such as beef, dairy, pork, and poultry, but also less common types such as sheep, bison, horses, etc., annual crops (e.g., wheat, canola, corn, various legumes and other small grain crops), pastures and grasslands. The model can also provide estimates of fuel and electricity demand (i.e., irrigation pumps) from farming operations and infrastructure.

The model estimates direct nitrous oxide (N2O), methane (CH4), and carbon dioxide (CO2) losses from the different farm components, and indirect losses as a consequence of ammonia (NH3) volatilization and nitrate (NO3-) leaching. In addition to these, the model includes ‘upstream’ estimates for emissions created through the production of farm inputs (e.g., CO2 losses from fertilizer, pesticide, and electricity production). This allows for the estimation of GHG emissions from farming systems, as well as commodity-based ‘cradle to farm-gate’ assessments that can be part of life cycle analyses.

While it is therefore an option to test the results of scientific experiments in a whole-farm context (under ‘what if?’ scenarios), it is the aim of the model to allow for the exploration of alternative management scenarios that may aid the decision-making processes of producers and policy makers alike (answering their ‘what if?’ questions). The model aims, thus, to provide an easy-to-use model for multiple users (including producers, researchers and policy makers), allowing them to investigate the impacts of on-farm practices, management decisions and policy interventions on GHG emissions.

With the development of version 4 of the model, the Holos team recognizes the need to further facilitate the holistic assessment of farms with additional components (i.e., on-farm wetlands, riparian buffers, woodlots, and renewable energy generation), as well as the need to provide additional capabilities (i.e., economics and ecosystem services modules). Although these components are not featured in Holos version 4, the future collaborative development of Holos version 5 has been facilitated by the open source availability of the version 4 model code. Thus, we are continually looking for opportunities to involve the expertise of other groups outside of AAFC to facilitate their inclusion in future versions.

## Target audience

There is not one single target user group for the Holos model, as the model aims to serve the needs of users from a variety of backgrounds and with different objectives. These objectives may be scientific in nature, related to policy making, or the user may wish to explore the impacts of alternative farm management decisions. In the latter sense, the model can also be used as an educational tool, opening up the user community to also include educators. The development team is aiming to increase the capabilities and usability of the model by providing options for collaborative development for computer science experts or multi-media artists.

Scientific use of the model concentrates primarily on the (re)assessment of results from scientific experiments, comparing emission measurements to the model outputs, or testing the effects of these experiments in the context of overall farm emissions. This has led to a number of peer-reviewed publications that have examined the emission sources in beef and dairy production systems, comparing past and present performance, and investigated the effect of feed ingredient choice on overall farm emissions. The latter involves the estimation of crop production emissions and carbon (C) storage potentials from crop production choices (e.g., reduction of tillage or planting of perennials). For scientific use, we expect a need for a high level of detailed data inputs that reflect the experimental setup.

Policy makers are likely to utilize the model for policy implementation, where farmers (land owners) input their farm operation data into the model and use the outputs (potentially through a certified 3rd party) as confirmation that the policy has been fulfilled. This requires certainty that the model algorithms work reliably (i.e., by alignment with national metrics), that the specific policy option can be modelled, and that the farmer (land owner) has all required input data available. Another option for the policy maker is, however, to test policies and their effects before implemention. For that purpose, the model requires appropriate regionally representative default farming systems (with all of the necessary input parameters) to test the policy under different settings.

For farmers, the model could be useful to self-explore where emissions come from on their farm, and how they compare in magnitude. In addition, they can explore management practices that lower emissions from the farm, altering individual practices or the entire farm system. Productivity changes due to management decisions are not included in the model, as the estimation of crop or animal growth would require additional inputs that are not readily available, and would also lead to considerable uncertainty (note that a simple economic model for cropping operations attempts to provide cost estimates for changing management, but is limited in scope and operability). Regardless of these limitations, farmers have used the model for self-assessments (‘what if?’) for marketing purposes.

The model has further application in agricultural education, particularly in courses concerned with sustainability. This serves both to showcase to students how interconnected production processes are in farming systems, and also to identify GHG sources in farming and the best options to reduce them effectively. The software development in itself has also proven to be an excellent teaching opportunity for individual computer science students who want to experience industry standard programming and code maintenance. Last but not least, the team is looking to partner with multimedia and arts students to improve the design and form of model inputs and outputs.

## Principles of model development

Development of the Holos model takes place in two phases: the development and combination of algorithms, and the transferral of these algorithms into software code in conjunction with the design of the interface. This is not necessarily a one-way street, both interface design and software development may trigger additional development (mainly due to opportunity rather than necessity). In any case, the Holos development team follows the two principles of transparency and scientific reliability in order to foster open and collaborative model and software development.

Scientific reliability is at the core of Holos algorithm development and means that the team attempts to build the model entirely out of algorithms and relationships that have been published in peer-reviewed articles, which have, where possible and/or required, a Canadian context. This approach does mean that the model will not be abreast of current scientific developments in the field, but rather that new knowledge will only be adopted when scientific consensus is built. Scientific reliability is also achieved through alignment with other metrics and assessment methods, with the National GHG inventory and AAFC’s Agri-environmental indicators being important benchmarks and algorithm providers. Lifecycle analysis standards (ISO 14044) also provide important guidance on how model results should be summarized. Scientific reliability and the opportunity to trace each algorithm to its published origin is also the foundation of the transparency principle.

In an attempt to avoid Holos model outputs being perceived as the result of ‘black box’ simulations, the Holos development team is releasing algorithm documents that detail each and every algorithm incorporated into the model (equation numbers in the document will match equation numbers in the software code). Algorithm documents track the progress of consecutive model versions, and in principle provide the basis for re-building the model in any other (software) environment. To further expand the transparency and adaptability of the model, the team is also preparing to share the model’s software code in an open source environment. This is with the goal of sharing the algorithm interconnectedness that is hard to relay in written documents, but also to open the model’s software code for collaborative additions by other groups, and for adaptation of the model by other groups for their specific objectives and requirements.

The Holos development team pledges to develop and share a framework for collaborative development with respect to software architecture, as well as documentation and data input requirements. However, the determination of what is included in subsequent Holos model versions remains with the Holos development team for the foreseeable future.

## Workshops and outreach

Modelling agricultural systems is a way to test our scientific understanding of processes taking place in these systems, to provide context to the results of scientific experiments, to understand and teach the interconnectedness of farm systems, to explore options and capabilities to influence the system and its outputs, and to guide and inform future research. Despite these benefits, modelling systems doesn’t come naturally to any of our potential user groups, and the team, therefore, provides multiple options to learn more about modelling and the model. These options range from organizing an annual workshop/conference (including a model training session), providing model training as invited course or seminar speakers, providing training upon request or online, developing and distributing training materials, hosting trainees for model training or development purposes, as well as conducting and publishing our own modelling studies.

Our annual event has evolved from an initial afternoon Holos release workshop with 10 participants to a two day ‘Sustainability of Canadian Agriculture’ conference with over 100 participants, where we bring together scientists, academics, farmers, farmer organizations, and policy makers to debate how Canadian farming can continue into the future, and, in this sense, how the Holos model and its team can help and support the community.

Model training has been provided on demand on multiple occasions, mostly upon invite from university partners, although the provincial government has also requested model training. Typically, the Holos team appreciates a formal invite (>2 months before the event) to organize travel (contact holos@agr.gc.ca). Training can be held for up to 50 participants (it is advisable that trainees work in pairs), and computers (Windows platform) should be available with the Holos model pre-installed. It is helpful if trainers (other than the Holos team) are familiar with the training to assist trainees. Training can also be provided through an online platform, although troubleshooting is more limited and there is less opportunity for feedback.

One element that would improve online training (and self-training for that matter) would be available training materials. The Holos team has distributed training manuals as PDF files (for Holos V3) in the past, but recognizes their limited use. While Holos V4 is much more user-friendly and self-explanatory, it also offers much more flexibility in the setup, both with respect to modelling modes as well as possible data input. The Holos team aims, therefore, to update already existing training materials and to share a series of training videos. The team is available to host trainees at the Lethbridge Research and Development Centre. The team also offers opportunities for students as part of the Canadian universities Co-op student program (primarily computer science students).

Last but not least, the Holos team conducts its own model application studies that aim to demonstrate how the model can be utilized. Publications relating to model development and model application are listed on our [Holos download page](http://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/holos-software-program/?id=1349181297838), but we have limited resources to find publications by other groups who utilized the model. We would therefore appreciate if you could send us a copy!

## Structure of this document

The Holos algorithm document provides a detailed description of the algorithms incorporated into the Holos model. It begins with the land management section (which is also the recommended path of model input for users), detailing at first the calculations for carbon change using the Introductory Carbon Balance Model (ICBM), and subsequently the IPCC Tier 2 carbon model (IPCC 2019), the current National GHG inventory approach and the default option in the Holos model. The final carbon section is the updated shelterbelt component, from where we plan to continue into the water budget (will be added after the release of Version 4). With the nitrogen (N) model, describe the multi-year N budget approach (compliant with the National GHG inventory as far as the emission estimates are concerned).

In the livestock sections (Chapters 3, 4 and 5), we separate beef cattle, dairy cattle, swine, sheep, poultry and other livestock, using an IPCC Tier 2 methodology for beef and dairy cattle and some poultry calculations, and a mostly IPCC Tier 1 methodology for all other livestock types.   
**Note:** throughout the document the term “livestock type” refers to the broad livestock categories included in the model, e.g., beef cattle, dairy cattle, swine, etc., while the term “animal group” refers to individual sub-groups of animals within each livestock type, e.g., beef cows, dairy heifers, sows, rams, turkey hens, etc.

This is followed by the new manure component, where we track the amount of manure in storage over time. Subsequently, the energy requirement calculations (and emissions) are detailed. The economics section is still under development, as we determine how to move forward from the initial economics component in Holos V3 (also to be added after the release of Version 4). The end of the document details the summation of the results, uncertainty estimates and reporting considerations, before finishing with references and appendices.

## Required input parameters

General considerations:

* **Leap years are not considered.**
* **Metric or imperial units of measurement are chosed at the start, and apply to the complete run.**
* **There is a French and an English version of the interface.**
* **All entered information saves instantaneously and continuously.**
* **The user can select each farm component multiple times.**
* **The default soil data are limited to the areas designated as containing agricultural land by Statistics Canada.**

### Map location

The first required model input is the selection of the farm’s location. The user first selects the relevant Canadian province, and then the specific longitude and latitude of the farm by clicking on the relevant location in the displayed map. Selecting the specific farm location also allows Holos (asas a default) to download a location-specific historic daily weather dataset from <https://power.larc.nasa.gov/data-access-viewer/>. These climate data are required for the ICBM (detailed in **section 2.1**), the IPCC Tier 2 carbon model (**section 2.2**), the calculation of nitrous oxide emissions (**section 2.5, 2.6, and 2.7**), and the estimation of emissions from livestock and their ammonia volatilization losses (**section 3 and 4**).

Each farm location will fall within a specific Soil Landscapes of Canada (SLC) polygon. The choice of SLC polygon allows the lookup of commonly present soil types in the region (<https://open.canada.ca/data/en/dataset/5ad5e20c-f2bb-497d-a2a2-440eec6e10cd>), permitting the user to choose the best fitting soil type (where more than one exists within a single SLC polygon), which is then applied as a default throughout the farm. In the same menu, on a different tab, the appropriate plant hardiness zone (PHZ) can be selected (<http://www.planthardiness.gc.ca/?m=1>), if more than one is present in the selected polygon. The PHZ is used for specific shelterbelt soil C and root growth lookup tables, with the exception of the province of Saskatchewan, where lookup tables are present for each ecodistrict (this is one case where the province selection triggers a province-specific lookup).

### Climate data

The resolution of climate data required by Holos varies depending on the model component. Daily climate data are needed for the calculation of ammonia loss and animal performance, as well as in the land management component to calculate the soil moisture, but the model is setup to run with monthly climate normals if daily data is not available..

For the ICBM, daily temperature and precipitation data are required for the estimation of soil temperature and as input to the soil moisture model; additionally, daily potential evapotranspiration data are required. Research conducted by Martel et al. (2018) found that the Turc (1961) equation was best suited to estimate actual evapotranspiration from Canadian farming systems, compared with measured data from an Eddy-flux system. These equations (in response to the relative humidity) are given below:

**For RH >= 50%**

**Eq. 1.6.2‑1**

**For RH < 50%**

**Eq. 1.6.2‑2**

Turc (1961) after Alexandris et al. (2008)[[1]](#footnote-2)

**Eq. 1.6.2‑3**

**For grasses, a non-linear function to calculate Kc is used.**

**Eq. 1.6.2‑4**

**Eq. 1.6.2‑5**

where

*ETr* Reference evapotranspiration (mm day-1)

*ETc* Crop specific evapotranspiration (mm day-1) without consideration of soil water availability

*Tmean* Mean daily temperature (℃)

*Rs* Solar radiation (MJ m-2 day-1)

*RHmean* Relative humidity (%)

*Kc*Growing degree day driven crop coefficients

*a, b, c, d, e* Coefficients required to calculate growing degree day driven crop coefficients (**Table 1**)

Holos V4 will use the following constant values:

Tbase 5 ℃ (Martel et al. 2018)

In order to reduce data input requirements for the user, the Holos model links to a repository of daily climate data from the NASA POWER data access viewer:

<https://power.larc.nasa.gov/data-access-viewer/>

Using this viewer, daily minimum and maximum temperature, precipitation, solar radiation, and relative humidity are downloaded for the specified location. Using these climate data (or alternative climate data uploaded by the user), Holos will calculate monthly climate normals to be used in the livestock components (all past years) and for the current and all projected years. The climate normals for the projection period can be iterated by the user to test their own climate scenarios.

To calculate monthly climate normals, the following generic equation is used:

**Eq. 1.6.2‑6**

where

*Climate\_Normal(type,period,month)* 30 year average of daily climate values for a certain *type*, *period*, and *month*

*Period* Range of years for which climate normals are calculated (**Table 2**)

*Month* Range of months for which climate normals are calculated (**Table 2**)

Type Maximum temperature (℃), minimum temperature (℃), mean temperature (℃), precipitation (mm), crop evapotranspiration (mm), relative humidity (%), solar radiation (MJ m-2)

*Startyear* Year in which a climate normal period starts (**Table 2**)

*Endyear* Year in which a climate normal period ends (**Table 2**)

*Startmonth* Julian day on which a month starts (**Table 2**)

*Endmonth* Julian day on which a month ends (**Table 2**)

### Land management

#### Field

1. Crop type grown (incl. cover crop) and field size are essential inputs, as these are needed to estimate N inputs from aboveground (i.e., straw) and belowground (i.e., roots) biomass to the soil. To carry out the necessary calculations, the model uses the input data together with in-built default data. If the user wants to specify a (repeating) cropping sequence/crop rotation, the crops planted in previous years also need to be specified.
2. Crop yield, amount of fertilizer applied, and residue return should be provided by the user if possible. In the absence of user-defined input for these parameters, the model will use default data, although these are only approximate representations.  
   - default crop yields are derived from Census Agricultural Regions (CAR) averages for the specified year (<https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210000201>).  
   - fertilization amounts (N) are calculated from crop N demand (based on the crop yield), assuming a fertilization efficiency of 50% (thus by default doubling the crop N demand)  
   - manure N and C additions are estimated from the livestock components or from literature derived averages.  
   - the residue return default for roots is 100% (for all crops except root crops), and straw return is assumed to be 100% (all straw remaining in the field). There are crop specific default harvest losses (2% for annual crops and 35% for perennial crops), but these are assumed to be of relatively minor importance in the calculation of C inputs.
3. Tillage regime, irrigation amount, and pesticide application rates are minor inputs for GHG emission estimates, as their impact is primarily driven by the emissions caused through fuel use. However, they are major cost elements in a farm system and will have more importance in the economics component. Atmospheric N deposition, N fixation, soil test N and fertilizer efficiency (to reduce the estimated N fertilization rate), and the moisture content of the crop at harvest can also be adjusted in the details settings.
4. Crop-specific biomass fractions and N concentrations are ‘hidden’ inputs that can be overwritten if specific or better data are available, but these are considered expert level changes and making these adjustments is not recommended.

#### Crop rotation

The crop rotation component only works in the *multi-year mode* of the model. It has the same input requirements as the field component, with the difference being that each added rotation phase (i.e., year) will automatically add one field with the same rotation, but with the crop sequence shifted by one year. This is done to maintain the principle that each rotation phase is present every year. The crop management practices specified are automatically applied on all fields, although these can be overwritten later in the time-line screen.

#### Shelterbelt

For the shelterbelt component, the current state of C accumulation can be calculated using row length, number of tress and their average circumference, as long as the shelterbelt species is specified. The age of the shelterbelt can also be defined. The model will provide outputs estimating the amount of C stored within the tree, and also C stored in the soil below. Projections into the future presume non-limited (ideal) growth if planted new, but if a below-average circumference is specified (for an existing shelterbelt), that reduction will perpetuate into future C accumulation estimates.

### Livestock management

The livestock management interface for all animal groups follows the same principle. In the first step, the user defines how many animal groups are in their system. Animals can be partitioned into groups with similar management practices, but if so desired, the management for individual animals can be specified. In the second step, users define the management periods for their system, again with the option to detail management practices for individual days if desired. The third step permits the user to specify the number of animals, their start weight and average daily gain. Model default values for the housing and manure management systems can be overwritten. Furthermore, diet quality can be defined, either by using the provided defaults, or by designing a new diet using the Custom Diet Creator. When choosing pasture as the housing system, an additional dropdown will enable the user to ‘place’ the animals onto one of the fields that have been added. This will trigger the model to calculate excreted manure as a C and N addition to that field.

#### Beef

The beef production system provides three components: the cow-calf component that is pre-setup to cover a full year, and the (at least initially) short-term backgrounding and finishing components. The cow-calf component has presets for cow/calf groups, replacement heifers and bulls, and preset management periods for winter feeding, summer grazing and extended fall grazing. Selecting pasture as the housing option for an animal group permits the user to select an existing field as the pasture. Carbon and N excreted by these animals during their time on pasture will be automatically added to the field’s C and N calculations.

Preset animal numbers, weights and weight gain, housing system, manure management and diets are also present. The is also the case for the backgrounding and finishing components, but note that only one management period is entered as default for these components. If the user wishes to explore emissions over a full year, they will have to add management periods to represent subsequent cattle generations.

The user should override these defaults as needed, with the primary focus (regarding the calculation accuracy of GHG emissions) on animal numbers and animal weights (and gain), followed by diet specifications, and the housing and manure management. Selecting “Show Additional Information” in the “Housing” tab also grants access to the bedding material calculator, and in the “Manure” tab this grants access to to several emission factors used in the model calculations. The latter should not be changed without scientific evidence.

#### Dairy

The dairy production system does not feature different components, but instead lists the different animal groups within a single component. However, group-specific management periods and practices are provided and can (and should) be overwritten by the user where locally specific data are available. In contrast to the beef components, milk production, milk fat content and milk protein should be specified by the user as this information will impact the energy requirement calculation, and thus the enteric methane estimates.

#### Pork

The pork/swine production system offers different components (or combinations thereof) to best represent Canadian farming systems (Farrow to Wean, Iso-Wean, Grower-to-Finish, and Farrow-to-Finish). The user should select the components that best represent their system. Only the Farrow-to-Wean and Farrow-to-Finish include Sow and Boar groups as default, but animal groups can be added to any component as needed. As it is common to switch diets based on weight during the different stages of growth, the default management periods are setup to represent expected changes in diet.

Note that the enteric CH4 emissions from pork are calculated using a per animal emission rate, specific to each animal group, therefore weight and daily gain information are not required. These emission factors can be adjusted when the user selects the “Show Additional Information” option, although these should only be changes based on scientific evidence, By default, the model assumes that all animals are housed in barns, but the housing system can be adjusted. Diet formulations can also be changed, but as mentioned above, this will not impact the CH4 emission rate until a method is developed that can account for such changes. However, changes in diet do impact C and N excretion in manure and emissions estimates.

#### Poultry

The poultry components represent different operations commonly present in Canada (Pullet Farm, Chicken Multiplier Breeder, Chicken Multiplier hatchery, Chicken Meat Production, Chicken Egg Production, Turkey Multiplier Breeder, and Turkey Meat Production), but these are more limited than the other livestock components due to the lack of a model that can take diet information into account. The model therefore does not required feed information at this time. Animal numbers, housing, and manure management are inputs that can be adjusted.

#### Sheep

The sheep components includes Rams, Lambs and ewes, and a Sheep feedlot. Input requirements are similar to the beef cattle and dairy components, however, we were unable to find data that would permit us to define default management periods. Other than in the sheep feedlot interface, wool production can be defined (adjusting energy requirements and thus enteric CH4 calculations). For the diets, the user can choose the preset default diets or define custom diets in the Custom Diet Creator.

#### Other livestock

All other livestock components use the IPCC Tier 1 (IPCC 2006,2019) methodology (default emission rates per animal), which is why only animal numbers and manure management information are needed. Manure excretion rates are currently estimated, so animals can be placed on pasture, but currently no biomass consumption rates are available.

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**Table 1**

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# Land Management

## Introductory Carbon Balance Model (ICBM)

(by R. Kröbel and A.W. Alemu)

The Introductory Carbon Balance Model (ICBM) is a simplified 2-pool C model developed to estimate soil C balance. The model is comprised of a ‘young’ C pool, receiving aboveground and belowground C inputs (e.g., straw, roots, and manure) which decay quickly. Part of the ‘young’ C ‘humifies’ (transfers) into the ‘old’ pool, which decays at a much slower rate.

Decay and humification factors are constant for each C fraction, and an adjustment parameter is calculated to model climate and management impacts (Andrén and Kätterer 1997). This climate/management factor (*re*) summarizes the external influences on soil biological activity and decomposition rates as a function of soil water content, soil temperature, and tillage intensity.

While the climate factor can be calculated using only climate data and by holding soil properties constant, Holos V4 uses soil properties and crop characteristics, in addition to climatic data in the calculation, based on a user-selected soil polygon. Soil characteristics are provided by the Soil Landscapes of Canada ISLC) version 3.2 (Soil Landscapes of Canada Working Group, 2010). For most soil polygons, Layer 1 characteristics are used. If Layer 1 is a litter layer, then Layer 2 characteristics are used.

Holos will download location-specific historic daily weather dataset from <https://power.larc.nasa.gov/data-access-viewer/> if an internet connection is available. If the internet cannot be accessed, Holos will fall back on internally stored monthly climate normals (average of the period 1980 – 2010) for temperature, precipitation and evapotranspiration that are specific to the SLC polygon the user has selected.

**Section 2.1.1.1** focuses on the climate factor (*re\_crop*), which represents the effects of soil water content and soil temperature, without the influence of tillage intensity. The *re\_crop* factor is subsequently multiplied by a tillage factor modifier (*rc*) prior to being used in ICBM equations to obtain the climate/management factor (*re*) (methodology in **sections 2.1.1.2** and **2.1.1.3**). The *re* factor is calculated for each field for each year of the defined simulation period, but will remain static for as long Holos V4 provided climate normals are being used.

The C input methodology is described in **Section 2.1.2**. Carbon inputs (in the presence of plant growth) are annual and differ with the type of plant grown. They consist of aboveground residues (straw and product) and belowground residues (roots and root exudates). In addition to selecting the type of crop, the farmer can provide additional C inputs by applying manure or additional crop residues, as well as deciding to not grow a crop (e.g., fallow the land), irrigate a grown crop for better growth, or change the intensity of tillage.

Changes in management result in changes to C inputs or to the previously described tillage factor modifier (*rc*). Management practices such as fallow and irrigation modify climatic factors in the *re\_crop* calculation. Crop residue C inputs to soil are a function of yield and residue management (Bolinder *et al.* 2007; Gan *et al.* 2009).

ICBM requires a starting point for initialization. **Holos Version 4 relies on the assumption that soil organic carbon (SOC) is in a steady state/reference condition in 1985 for the rotation and management practices described (Kröbel et al., 2016).** Multi-year crop rotations complicate this initialization because of differing C inputs depending on crop type. As such, the C input used will be the average of all C inputs from all crops in the described rotation. Initialization at steady state is described in **section 2.1.3**. The user also has the option to input a measured starting SOC value, which will override the default steady state condition.

### Climate and management factors influencing carbon decomposition

#### Climate Factor (*re\_crop*)

The *re\_crop* factor is calculated daily and expressed as a mean annual average value for use in further ICBM equations. When there is no internet connection and daily climate data cannot be downloaded from the NASA website, Holos V4 uses the 30 year normal climate values for each month. The monthly mean temperature value is used for each day of the month in the parameter calculations. The monthly precipitation and evapotranspiration value are divided by the number of days in the month and used for each day of the month. The *re\_crop* methodology follows that described in Bolinder et al. (2008) and Kätterer and Andrén (2009). The following equations are calculated each day for 365 days of the year.

##### Green area index dynamics

**Eq. 2.1.1‑1**

**Eq. 2.1.1‑2**

**Eq. 2.1.1‑3**

where

*GAImax* Maximum amplitude of green area index

*Yield* Crop yield (kg dry matter (DM) ha-1, database default or user specific)

*MidSeason* Median day of growing season (Julian day)

*EmergenceDay* Day of crop emergence (Julian day)

*RipeningDay* Day of crop ripening (Julian day)

*GAI* Green area index

*JulianDay* Day (Julian day)

*Variance* Width of distribution function

Holos V4 will use the following constant values:

*For annuals:*

EmergenceDay 141

RipeningDay 197

Variance 300

*For perennials:*

EmergenceDay 75

RipeningDay 300

Variance 1500

##### Water content at wilting point and field capacity

**Eq. 2.1.1‑4**

**Eq. 2.1.1‑5**

**Eq. 2.1.1‑6**

**Eq. 2.1.1‑7**

**Eq. 2.1.1‑8**

where

*OrgCfactor* Organic C factor

*SoilOrganicCPercent* Percentage of organic C in soil, by weight (%, SLC data table)

*Clayfactor* Clay factor

*ClayContent* Proportion of clay in soil (SLC data table)

Sandfactor Sand factor

*SandContent* Proportion of sand in soil (SLC data table)

*WiltingPointPercent* Water content at wilting point (%)

*WiltingPoint* Proportion of water content at wilting point (mm3 mm-3)

*FieldCapacityPercent* Water content at field capacity (%)

*FieldCapacity* Proportion of water at field capacity (mm3 mm-3)

**Eq. 2.1.1‑9**

**Eq. 2.1.1‑10**

where

*OrgCfactor* Organic C factor

*SoilOrganicCPercent* Percentage of organic C in soil, by weight (%, SLC data table)

*Clayfactor* Clay factor

*ClayContent* Proportion of clay in soil (SLC data table)

Sandfactor Sand factor

*SandContent* Proportion of sand in soil (SLC data table)

*WiltingPointPercent* Water content at wilting point (%)

*WiltingPoint* Proportion of water content at wilting point (mm3 mm-3)

*FieldCapacityPercent* Water content at field capacity (%)

*FieldCapacity* Proportion of water at field capacity (mm3 mm-3)

##### Soil temperature

The soil temperature algorithms involve a series of looping equations based on soil temperature the previous day.

**Eq. 2.1.1‑11**

**Eq. 2.1.1‑12**

where

*SoilMeanDepth* Soil mean depth (mm)

*SoilTopThickness* Thickness of top layer (mm)

*LeafAreaIndex* Leaf area index

Holos V4 will use the following constant values:

SoilTopThickness 250mm

###### Surface Temperature

If Temperature < 0˚C

**Eq. 2.1.1‑13**

If Temperature >= 0˚C

**Eq. 2.1.1‑14**

where

*Temperature* Daily mean air temperature (˚C, by month - SLC data table)

*SurfaceTemp* Soil surface temperature (˚C)

###### Soil Temperature

On Day 1 (if JulianDay = 1)

**Eq. 2.1.1‑15**

**After Day 1 (if JulianDay > 1)**

**Eq. 2.1.1‑16**

where

*SoilTemp* Soil temperature (˚C)

##### Water Balance

The water balance algorithms involve a series of looping equations based on water storage in the topsoil the previous day.

###### Irrigation

Default irrigation is only calculated when PE > P

**Eq. 2.1.1‑17**

where

*Irrigationannual* Annual irrigation, either calculated as default, or specified by the user (mm yr-1)

*PE* Annual evapotranspiration (mm yr-1)

*P* Annual precipitation (mm yr-1)

The amount of irrigation water applied to the crop daily is estimated as the proportion of total annual irrigation water applied each month (as specified by the model user) divided by the number of days in the month:

**Eq. 2.1.1‑18**

where

*Pdaily* Daily precipitation (mm d-1)

*Irrigationannual* Annual irrigation, either calculated as default, or specified by the user (mm yr-1)

*Fractionmonthly* Assumed monthly distribution of irrigation (%) detailed in **Table 4**.

*Daysmonth* Number of days per month

*Daily\_PrecipTotal* Combined moisture input per day (mm d-1)

The proportion of the annual irrigation amount applied in each month and for each province is estimated as an average of values derived from the Agricultural Water Use Survey for 2010 and 2012 (Statistics Canada, 2013a,b) (**Table 4**).

###### Crop Evapotranspiration

**Eq. 2.1.1‑19**

**Eq. 2.1.1‑20**

where

*Kc* Crop coefficient (calculated according to Martel et al., 2021 – see **section 1.6.2**)

*ETc* Crop evapotranspiration under standard conditions (mm day-1)

*ETo* Daily reference crop evapotranspiration (mm day-1 - SLC data table)[[2]](#footnote-3)

###### Soil Available Water

If *Daily\_PrecipTotal* < 0.2\*GAI

**Eq. 2.1.1‑21**

If *Daily\_PrecipTotal* >= 0.2\*GAI

**Eq. 2.1.1‑22**

If *CropInterception* > ETc

**Eq. 2.1.1‑23**

**Eq. 2.1.1‑24**

**Eq. 2.1.1‑25**

If *VolSoilWaterContent* = 0 or n.a.

**Eq. 2.1.1‑26**

where

*CropInterception* Crop interception[[3]](#footnote-4) of precipitation + irrigation[[4]](#footnote-5) (mm day-1)

*Daily\_PrecipTotal* Daily precipitation + irrigation (mm day-1 - SLC data table)

*SoilAvailWater* Soil available water (mm day-1)

*VolSoilWaterContent* Volumetric soil water content (mm3 mm-3)

*WaterStorage* Water storage in topsoil (mmday-1) – calculated previous day in **Eq. 2.1.1‑32**

###### Actual Evapotranspiration

**Eq. 2.1.1‑27**

***Kr* ranges from 0 to 1.**

**Eq. 2.1.1‑28**

If VolSoilWaterContent < alfa/100\*WiltingPoint

**Eq. 2.1.1‑29**

**Eq. 2.1.1‑30**

where

*Kr* Soil coefficient (dimensionless)

*alfa* MMinimum water storage fraction of WiltingPoint

*ETa* Actual evapotranspiration (mm day-1)

Holos V4 will use the following constant values:

alfa 0.7

###### Water Storage

On Day 1 (if *JulianDay* = 1)

**Eq. 2.1.1‑31**

**Eq. 2.1.1‑32**

After Day 1) (if *JulianDay* > 1)

**Eq. 2.1.1‑33**

If DeepPerc < 0

**Eq. 2.1.1‑34**

**Eq. 2.1.1‑35**

where

*DeepPerc* Water lost to percolation down the soil profile (mm day-1)

##### Decomposition rate – effect of soil temperature

**Eq. 2.1.1‑36**

If *SoilTempd-1* < -3.78 ˚C

**Eq. 2.1.1‑37**

where

*re\_temp* Temperature response factor

*Tempmin* Critical soil temperature (˚C)

*Tempmax* Maximum soil temperature (˚C)

Holos V4 will use the following constant values:

Tmin -3.78°C

Tmax 30°C

##### Decomposition rate – effect of soil moisture

**Eq. 2.1.1‑38**

**Eq. 2.1.1‑39**

If VolSoilWaterContent > VolSoilWaterContentopt

**Eq. 2.1.1‑40**

If VolSoilWaterContent < WiltingPoint

**Eq. 2.1.1‑41**

If WiltingPoint <= VolSoilWaterContent <= VolSoilWaterContentopt

**Eq. 2.1.1‑42**

*re\_water* ranges from 0 to 1.

**Eq. 2.1.1‑43**

where

*VolSoilWaterContentsat* Volumetric soil water content at saturation level (mm3 mm-3)

*VolSoilWaterContentopt* Volumetric soil water content at optimal water content (mm3 mm-3)

*rs* Reference saturation (mm3 mm-3)

*rwp* Reference wilting point (mm3 mm-3)

*re\_water* Moisture response factor

Holos V4 will use the following constant values:

rs 0.42 mm3 mm-3

rwp 0.18 mm3 mm-3

##### Climate Factor

*re\_crop* will be calculated daily and expressed as a mean annual average value for use in ICBM equations.

**Eq. 2.1.1‑44**

**Eq. 2.1.1‑45**

**Eq. 2.1.1‑46**

where

*Reference adjustment* Calibration factor for a bare-fallow treatment considering a soil thickness of 25 cm, (Uppsala, Sweden)

*re\_crop* Climate parameter

Holos V4 will use the following constant values:

Reference adjustment 0.10516

#### Tillage Factor (*rc*)

Using a dynamic C model that starts in 1985, tillage is specified for each simulation year, and changes in tillage are incorporated through an iterated decomposition adjustment factor (*rc*).

Required user input: Current tillage regime per rotation and/or crop, Past tillage regime for any previous rotation or crop, Year of change

Tillage options: No-till, Reduced tillage, Intensive tillage

Tillage can be modified for each year of the cycle and is based on user input. For the Prairie Provinces (Alberta, Saskatchewan, and Manitoba), changes in tillage management have been shown to influence soil C stocks. Accordingly, the tillage factor varies with soil type and tillage intensity.

For perennials in the prairie provinces (Alberta, Saskatchewan and Manitoba), as a default the no-till factor for the relevant soil type is applied in all years of the stand except for the final year (year in which the crop is terminated), in which the reduced tillage factor is applied for the relevant soil type (**Table 3**). For all non-prairie provinces, the constant values in the box below are used.

Holos V4 will use the following constant values:

*rc* for annuals 1.0 (default for non-prairie provinces)

*rc* for perennial crops 0.9 (default for non-prairie provinces, M. Bolinder, per. comm.)

*rc* for root crops 1.13 (for all provinces and soil types)

#### Climate/management Factor (*re*)

The climate/management factor (*re*) is calculated annually for each field for each year of the simulation period.

**Eq. 2.1.1‑47**

where

*re* Climate/management factor

*rc* Tillage factor

### Carbon inputs

Carbon inputs are calculated for each field for each year of the simulation period following the methodology described by Bolinder et al.(2007). The methodology differs between annual and perennial crops. Furthermore, silage crops are handled uniquely, as are root crops. Carbon inputs from product, straw, root, and extra-root are characterized by crop, with the first two being assigned to the aboveground residue pool, and the latter two to the belowground residue pool. **It is assumed that extra-root C (representing the root exudates a plant releases into the soil environment) is a fixed proportion of plant C for all crop types (i.e., 65%).**

Note that irrigated and rainfed crops have different biomass allocation coefficients. The Holos model will include specific biomass fractions for irrigated crops where available, and use standard fractions as defaults where no specific information is available.

#### Above- and belowground residue input

As the model requires data on harvest losses, we assume that the measured yield provided by the user represents the collected harvest after the loss took place. Therefore, the user provided yield is updated to include the amount of harvested product lost during harvest – this loss is assumed to be 2% for annual crops and 35% for perennial crops. The total yield estimate (including harvest losses) is then adjusted to account for moisture content to provide a dry matter yield value:

**Eq. 2.1.2‑1**

*where*

*Cp* Plant C in agricultural product (kg ha-1)

*Yield* Crop yield (kg wet weight ha-1, default provided, user override)

*moisturecontent* Moisture content (%) of crop product (**Table 7**)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)[[5]](#footnote-6)

*Sp* Percentage of product yield returned to soil (user override)

*For annual crops, perennial crops, and fodder corn.*

**Eq. 2.1.2‑2**

**Eq. 2.1.2‑3**

*For root crops.*

**Eq. 2.1.2‑4**

**Eq. 2.1.2‑5**

where

*Cag* Aboveground residue C input (kg ha-1)

*CptoSoil* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*Cbg* Belowground residue C input (kg ha-1)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

**NOTE:** The amount of residues not returned to the soil is accounted for in the parameter **.**

#### Annual crops

Annual crops include small-grain cereals, oilseeds, pulse crops, and grain corn (**Table 7**).

**Eq. 2.1.2‑6**

**Eq. 2.1.2‑7**

**Eq. 2.1.2‑8**

**Eq. 2.1.2‑9**

where

*Cp* Plant C in agricultural product (kg ha-1)

*CptoSoil* C input from product (kg ha-1)

*Sp* Percentage of product yield returned to soil (user override)

*Cs* C input from straw (kg ha-1)

*Rs* Relative biomass allocation coefficient for straw (**Table 7**)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Ss* Percentage of straw returned to soil (user override)

*Cr* C input from roots (kg ha-1)

*Rr* Relative biomass allocation coefficient for roots (**Table 7**)

*Sr* Percentage of roots returned to soil (user override)

*Ce* C input from extra-root material (kg ha-1)

*Re* Relative biomass allocation coefficient for extra-root material (**Table 7**)

When green manure is chosen as a harvest option for a main crop (meaning the user is entering an aboveground biomass value instead of a grain yield), the residue fractions for product and straw are combined to form a single coefficient, Rp, and **Eq. 2.1.2‑6** is omitted from the calculations.

Holos V4 will use the following constant values:

*Carbonconcentration* 0.45 kg kg-1

SP 2% for annual crops, 35% for hay (haying loss)

Ss 100% for annual crops

Sr 100%

#### Silage Crops

Silage crops must be handled separately as these are annual crops yet function as a forage or perennial crop in that straw inputs are not calculated (i.e., all aboveground biomass is considered to be product). Therefore, for these crops, when specifying the yield, the user must enter a value for total aboveground biomass (kg aboveground biomass ha-1). **Table 7** provides a single combined product fraction (Rp) that accounts for all aboveground biomass. Silage crops include: corn silage, barley silage, triticale silage.

**Eq. 2.1.2‑10**

**Eq. 2.1.2‑11**

**Eq. 2.1.2‑12**

**For crops where no lookup value is available, the default grain yield (for the respective cash crop) is used to calculate the total aboveground dry matter (product + straw/residue). Note: Eq. 2.1.2‑13 is calculated only for those silage crops listed in the drop-down “Crop” menu in Holos (barley, oat, corn, triticale and wheat silage):**

**Eq. 2.1.2‑13**

where

*Yieldsilagecrop* Estimated yield (kg DM ha-1) of total aboveground biomass (product + straw/residue) for silage crop

*Yieldgraincrop* Yield (kg wet weight ha-1, user reported or default value) of corresponding grain crop (product)

*Rs* Relative biomass allocation coefficient for straw/residue (**Table 7**)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Sp* Percentage of product yield returned to soil as harvest loss (user override)

*moisturecontent* Moisture content of the grain crop (%)

Holos V4 will use the following constant values:

*Carbonconcentration* 0.45 kg kg-1 (Baron et al., 2002)

SP 2%

Sr 100%

#### Cover Crops

Cover crops are defined as a secondary crop grown after a main crop, outside of the growing season. As there is a variety of conflicting or simultaneous utilizations for such crops (e.g. soil cover, green manure, forage, produce), we assumed a number of default fractions for C return (see box below), which the user can override.

In the case where a ‘cover crop’ is used instead of a bare fallow (In the Canadian prairies), the user is requested to input that as a main crop. Thus, the overall yield and the provided main crop biomass fraction have to be adjusted to represent the grown cover crop as replacement of a main crop.

**Eq. 2.1.2‑14**

**Eq. 2.1.2‑15**

**Eq. 2.1.2‑16**

where

*Cp* Plant C in agricultural product (kg ha-1), calculated using **Eq. 2.1.2‑1**

*CptoSoil* C input from product (kg ha-1)

*Sp* Percentage of product yield returned to soil (user override)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Cr* C input from roots (kg ha-1)

*Rr* Relative biomass allocation coefficient for roots (**Table 7**)

*Sr* Percentage of roots returned to soil (user override)

*Ce* C input from extra-root material (kg ha-1)

*Re* Relative biomass allocation coefficient for extra-root material (**Table 7**)

Where cover crops are used as green manure, forage, or biomass crops, the crop yield is entered as total aboveground biomass (kg ha-1). In this case, fractions of product (Rp) and straw (Rs) are combined into Rp, and **Eq. 2.1.2‑14** is omitted. Where the cover crop is harvested as a cash crop (e.g., winter wheat), the calculations are the same as those for annual cash crops with separate Rp and Rs (and **Eq. 2.1.2‑14** is included).

Holos V4 will use the following constant values:

*Carbonconcentration* 0.45 kg kg-1

SP – cover crop 100%

SP – forage 35%

SP – produce 0%

Ss 100%

Sr 100%

#### Root crops

Root crops (**Table 7**) follow the same basic methodology as described. However, the “root” is the product with these crops. As such, the methodology is modified as below.

**Eq. 2.1.2‑17**

**Eq. 2.1.2‑18**

**Eq. 2.1.2‑19**

where

*Cp* Plant C in agricultural product (kg ha-1)

*CptoSoil* C input from product (kg ha-1)

*Sp* Percentage of product yield returned to soil (user override)

*Cs* C input from straw (kg ha-1)

*Rs* Relative biomass allocation coefficient for straw (**Table 7**)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Ss* Percentage of straw returned to soil (user override)

*Ce* C input from extra-root material (kg ha-1)

*Re* Relative biomass allocation coefficient for extra-root material (**Table 7**)

Holos V4 will use the following constant values:

*Carbonconcentration* 0.45 kg kg-1

SP 0%

Ss 100%

#### Perennial crops

**Handling perennial crops**

Perennial crops follow the same basic methodology as annual crops. However, root growth and residue biomass allocation must be modified to account for the perennial nature of these crops (the term root turnover is introduced in addition to the root biomass, designating a fraction of the root biomass that is lost each year and regrown the next). Further, because the “straw” is generally the product with perennial crops (i.e., all aboveground biomass is product), the methodology is further adjusted with straw inputs removed. **Table 7** provides a single combined product fraction (Rp) that accounts for all aboveground biomass.

**It is assumed that 30% of the root biomass is turned over (input) annually before harvest, and 100% on harvest.** Extra-root input is calculated annually with the complete allocation coefficient.

Perennial crops include forages (**Table 7**).

For managed pasture, rangeland, and grasslands, the methodology is similar to the perennial crop calculations. Root growth and residue biomass allocation must be modified to account for the perennial nature of these crops. Further, because the “straw” is generally the product with perennial crops (i.e., all aboveground biomass is product); the methodology is further adjusted with straw inputs removed.

##### Aboveground biomass

See **section 11.3.2** for the calculation of C inputs after grazing or haying.

**In all years where no harvest amount is input by the user (it is assumed that growth takes place, but was too little to be harvested), aboveground growth/productivity is still calculated and aboveground return is automatically set to 100%.**

**In the first year (t) – including when underseeded:**

If Cp is provided by the user (Cp(t) > 0)

**Eq. 2.1.2‑20**

where

*Cp* Plant C in agricultural product (kg ha-1)

*Cptosoil* C input from product (kg ha-1)

*Sp* Percentage of product yield returned to soil (user override)

If Cp is unknown (Cp(t) = 0), but is available in the second year (Cp(t+1) > 0)

**Eq. 2.1.2‑21**

If Cp is unknown (Cp(t) = 0), and unknown in the second year (Cp(t+1)=0)

**Eq. 2.1.2‑22**

Thorpe (2011)

**Eq. 2.1.2‑23**

**Eq. 2.1.2‑24**

**Eq. 2.1.2‑25**

where

*Cp* Plant C in agricultural product (kg ha-1)

*CptoSoil* C input from product (kg ha-1)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*Sp* Percentage of product yield returned to soil (user override)

*P* Annual precipitation

*PET* Annual potential evapotranspiration

*MaySept* Proportion of annual precipitation falling in May through Sept

**In the following years (t>1):**

If Cp is unknown in any year but the first (Cp(t>1) = 0)

**Eq. 2.1.2‑26**

**Eq. 2.1.2‑27**

where

*Cp* Plant C in agricultural product (kg ha-1)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*CptoSoil* C input from product (kg ha-1)

*Sp* Percentage of product yield returned to soil (user override)

*P* Annual precipitation

*PET* Annual potential evapotranspiration

*MaySept* Proportion of annual precipitation falling in May through Sept

##### Belowground biomass

**In the first year/seeding year (t):**

**Eq. 2.1.2‑28**

**Eq. 2.1.2‑29**

where

*Cp* Plant C in agricultural product (kg ha-1)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Cr* C input from roots (kg ha-1); *Cr* must be equal to or greater than 450 kg ha-1 year-1 (i.e., root biomass must be equal to or greater than 1,000 kg DM ha-1 yr-1)

*Rr* Relative biomass allocation coefficient for roots (**Table 7**)

*Sr* Percentage of roots returned to soil per year

*Ce* C input from extra-root material (kg ha-1)

*Re* Relative biomass allocation coefficient for extra-root material (**Table 7**)

**In years t=2 to t=5 (inclusive):**

**Eq. 2.1.2‑30**

**Eq. 2.1.2‑31**

If Cr(t) < Cr(t-1):

**Eq. 2.1.2‑32**

**Eq. 2.1.2‑33**

where

*Cp* Plant C in agricultural product (kg ha-1)

*Rp* Relative biomass allocation coefficient for product (**Table 7**)

*Cr* C input from roots (kg ha-1) in year *t*

*Cr(t-1)* C input from roots (kg ha-1) in year *t-1*

*Percentrootincrease* Annual percentage increase in root biomass (%); a default constant *PercentRootIncrease* value of 19.35% is used for year t=2 to year t=5 (inclusive). **Note:** if the perennial stand endures beyond year t=5, then for all years t>5: Cr(t) = Cr(t-1)

*Ce* C input from extra-root material (kg ha-1)

*Re* Relative biomass allocation coefficient for extra-root material (**Table 7**)

##### Supplemental Hay

Holos V4 will use the following constant values:

*Carbonconcentration* 0.45 kg kg-1

SP 35% (haying loss)

Sp see **Table 60**

Sr 100% in the termination year and 30% in all other years

When supplemental hay is provided to grazing animals on pasture, C is added to the soil via feeding losses. A default feeding loss of 20% is used (Rotz and Muck, 1994). The addition of C to the soil via ‘lost’ supplemental hay is calculated as follows:

**Eq. 2.1.2‑34**

where

*Csupphay* C added to the soil in supplemental hay (kg ha-1)

*Baleweight* Weight of hay bale (kg) – user defined

*Balenumber* Number of bales provided as supplemental feed to grazing livestock on pasture – user defined

*Lossfeeding* Percentage of supplemental hay fed to livestock grazing on pasture that is ‘lost’. A default of 20% is used

*moisturecontent* Moisture content of hay (**Table 7**)

*Carbonconcentration* C concentration of hay. A default value of 0.45 kg kg-1 is used

#### Fallow

Fallowing will be handled as an annual crop with Yield=0, and for Western Canada, with a no-till tillage factor (e.g., 0.6 - 0.8 according to soil zone). The *re­­\_crop* calculation (**2.1.1.1**) will also use Yield=0. The user will be asked whether theythey are utilizing chemical fallow (at which point nothing further changes in the calculations, except the addition of herbicide usage driven emissions) or mechanical fallow (at which point, for Western Canada, a tillage factor will be assigned as listed in [**2.1.1.2**](#_Tillage_Factor_(rc))).

Required user input: Length and frequency of fallow phase in a crop rotation (or on a field), applied tillage or herbicide for weed control

Holos V4 will use the following default values:

*Yield* 0 kg ha-1

Tillage intensity no-till

#### Manure carbon inputs

The Holos model livestock calculations estimate the amount of manure excreted, and the manure is either applied directly to land (i.e., fresh or raw) or accumulates in the designated storage unit over time and is then applied to the farm’s fields. The user indicates in the cropping interface when and at what rate the manure is being applied (this is also the case when manure is imported to the farm from different sources). Holos uses Table 6 to derive default model inputs (e.g., manure C and N concentration) for each manure and storage type. However, as the moisture content is likely the most variable value, the user can input an approximate estimate of the actual moisture content to reduce the uncertainty of nutrient content calculations. The user will also be asked to specify the application method (if different to the default), however, this has no relevance for the C stock calculations. It is assumed that manure storage systems are empty at the end of the year thus any leftover manure remaining is equally spread across all of the farm’s fields (except native rangeland, if present) and relevant emissions are calculated.

Inputs of C to agricultural soils in fresh or stored livestock manure (i.e., dung, urine and bedding) are estimated in **Section 4.7** – see **Eq. 4.7.1‑6** for additions of manure C to soil in field *n* in year *t*. Inputs of C in anaerobic digestate applied to field *n* in year *t* are estimated in **Section 4.9.7.1 (Eq. 4.9.7‑5)** and inputs in dung and urine deposited directly on pasture by grazing animals are estimated in **Chapter 5 (Eq. 5.6.1‑1)**, specific to field *n* in year *t* - Note: this includes C added to soil by all livestock types grazing on field *n* in year *t*, and these amounts are exclusive of any CH4-C losses related to the deposition of dung and urine to soil by grazing animals.

#### Default biomass fractions

The default crop-specific biomass allocation fractions used in the ICBM are detailed in **Table 7**.

### Steady state

Holos Version 4 assumes an organic soil C steady state was achieved in the first year of the model simulation (default starting year: 1985). The year 1985 was chosen as a default start year as this was deemed the minimum time frame in which to assess C change due to management choices, as C changes take place over decadal time scales. This year also marks a time point before the rapid expansion of canola in the planting area, which subsequently may have lowered the overall variability of crop rotations and crops grown. This simplification was made to circumvent:

* that the user would have to supply a C stock value for their fields from 1985; and
* that crop rotation comparisons are confounded by the C model responding to a previous management change.

Using the initial historical (and field-specific) rotation provided by the user (the rotation described as starting in 1985 or an alternative start year specified by the user), Holos calculates average C inputs across the rotation for aboveground residue, belowground residue, and manure. The equations for the calculation of the steady state (soil C equilibrium) were newly derived by Dr. H.H. Janzen (2017, pers. Comm.) based on past ICBM literature (Andrén and Kätterer 1997).

Therefore, the model simulation starts in a steady state (equilibrium), and this steady state will be maintained for as long as the initial rotation is maintained with the same C inputs. Changes in soil C will only happen if the C inputs change, either through user specified annual crop yields, or by changing the crop rotation to include crops that have a different C input (see also Kröbel et al. 2016).

#### Average carbon inputs (default mode for cropping systems comparisons)

Carbon input from product and C input from straw (if an annual crop) is averaged for each crop in the rotation described in the simulation start year until the end of that management period to determine aboveground biomass C input.

Carbon input from roots and C input from extra-root material is averaged for each crop in the rotation described in the simulation start year until the end of that management period to determine belowground biomass C input.

Note that product from root crops is considered belowground biomass input – see section 2.1.2.5.

**Eq. 2.1.3‑1**

**Eq. 2.1.3‑2**

**Eq. 2.1.3‑3**

where

*Cag(rot)* Average aboveground residue C input (kg ha-1) of a rotation

*Cbg(rot)* Average belowground residue C input (kg ha-1) of a rotation

*Cm(rot)* Average manure (incl. manure deposited directly on pasture by grazing animals) + digestate C input (kg ha-1) of a rotation

*CptoSoil(rotationphase)* C input from product (kg ha-1) of each rotation phase

*Cs(rotationphase)* C input from straw (kg ha-1) of each rotation phase

*Cr(rotationphase)* C input from roots (kg ha-1) of each rotation phase

*Ce(rotationphase)* C input from extra-root material (kg ha-1) of each rotation phase

*Cm(rotationphase)* C input from manure and anaerobic digestate (kg ha-1) of each rotation phase, derived from **Eq. 4.7.1‑6** (for farm-produced and imported manure), **Eq. 4.9.7‑5** (for digestate) and **Eq. 5.6.1‑1** (for dung and urine deposited on pasture); this is a field-specific value calculated across all years in the first phase of the rotation

#### Young pool steady state

**Eq. 2.1.3‑4**

**Eq. 2.1.3‑5**

**Eq. 2.1.3‑6**

where

*Yag-ss* Young pool steady state - aboveground (kg ha-1)

*Ybg-ss* Young pool steady state - belowground (kg ha-1)

*Ym-ss* Young pool steady state - manure (kg ha-1)

*Cag(rot)* Average aboveground residue C input (kg ha-1) of a rotation

*Cbg(rot)* Average belowground residue C input (kg ha-1) of a rotation

*Cm(rot)* Average manure (incl. manure deposited directly on pasture by grazing animals) + digestate C input (kg ha-1) of a rotation

*ky* Decomposition rate constant for young pool

*re* Climate/management factor

Holos V4 will use the following constant values:

*ky* 0.8

#### Old pool steady state

**Eq. 2.1.3‑7**

where

*Oss* Old pool steady state (kg ha-1)

*hag* Humification coefficient – aboveground input

*hbg* Humification coefficient – belowground input

*hm* Humification coefficient – manure

*Cag(rot)* Average aboveground residue C input (kg ha-1) of a rotation

*Cbg(rot)* Average belowground residue C input (kg ha-1) of a rotation

*Cm(rot)* Average manure (incl. manure deposited directly on pasture by grazing animals) + digestate C input (kg ha-1) of a rotation

*ky* Decomposition rate constant for young pool

*ko* Decomposition rate constant for old pool

Holos V4 will use the following constant values:

*hag* 0.125

*hbg* 0.3

*hm* 0.31 (Kätterer & Andrén, 1999)

*ky* 0.8

*ko* 0.00605

*re* Climate/management factor

#### Measured starting soil organic carbon

If the user has a measured SOC value (kg C ha-1) that can be used to initialise the model, this can be entered as a custom starting value. This custom SOC value can be field-specific. Entering this value will override the default the steady state calculation before the first year of the simulation described above. Using the custom SOC starting value, the model estimates the size of the above- and belowground young C pools and the old C pool for the start of the simulation (year 0) as follows:

**Eq. 2.1.3‑8**

**Eq. 2.1.3‑9**

**Eq. 2.1.3‑10**

#### Soil organic carbon change

Using the ICBM (Kätterer *et al.* 2008), Holos will calculate C dynamics from the 1985 steady state or custom measured SOC onwards through the historical period (1985 to initial year of cycle) and through the present cycle. Holos can also project into the future to simulate soil C changes under user-defined scenarios.

**If there has been no change in management since the initial year of the simulation, Holos will assume no soil C change** (as per ICBM calculations), if the user does not specify annually specific (measured) yield values.

#### Soil organic carbon change – per hectare

The first C change calculation occurs in the second year of the simulation, and for this initial calculation t-1 values for young and old C pools should be steady state values as calculated in **Eq. 2.1.3‑4** - **Eq. 2.1.3‑6** or based on a measured initial SOC value as calculated in **Eq**. **2.1.3‑10**.

For the historical period (1985-year prior to initial year of cycle), average C input values will be used (**Eq. 2.1.3‑1** - **Eq. 2.1.3‑3**).

For the current cycle (from initial year to end of cycle), actual C input values will be used (**Eq. 2.1.2‑2** - **Eq. 2.1.2‑5**).

The manure pool acts as a young pool similar to the aboveground and belowground residue pools (see below).

**Eq. 2.1.3‑11**

**Eq. 2.1.3‑12**

**Eq. 2.1.3‑13**

The inclusion in the old pool calculation is based on (see further below):

**Eq. 2.1.3‑14**

**Eq. 2.1.3‑15**

**Eq. 2.1.3‑16**

where

*Yag* Young pool soil organic C – aboveground (kg C ha-1)

*Ybg* Young pool soil organic C – belowground (kg C ha-1)

Ym(t) Young pool soil organic C – manure (kg C ha-1)

*t* Current time step

*t-1* Previous time step

*Cag* Aboveground residue C input (kg C ha-1)

*Cbg* Belowground residue C input (kg C ha-1)

*Cm* C input from manure and anaerobic digestate (kg C ha-1) of each rotation phase, derived from **Eq. 4.7.1‑6** (for farm-produced and imported manure), **Eq. 4.9.7‑5** (for digestate) and **Eq. 5.6.1‑1** (for dung and urine deposited on pasture))

*re* Climate/management factor

*O* Old pool soil organic C (kg ha-1)

*hag* Humification coefficient – aboveground input

*hbg* Humification coefficient – belowground input

*hm* HHumification coefficient – manure input

*ky* Decomposition rate constant for young pool

*ko* Decomposition rate constant for old pool

*SOC* Soil organic C (kg ha-1)

Δ*SOC* Change in soil organic C from time *t-1* to time *t* (kg ha-1)

Holos V4 will use the following constant values:

*hag* 0.125

*hbg* 0.3

*hm* 0.31 (Kätterer & Andrén, 1999)

*ky* 0.8

*ko* 0.00605

#### Soil organic carbon change – per field, per farm

In order to calculate the C change per field and per farm, the area of the fields must be considered.

**Eq. 2.1.3‑17**

**Eq. 2.1.3‑18**

where

Δ*SOC(t)field* Change in SOC from time *t-1* to time *t* for field (kg)

Δ*SOC(t)* Change in SOC from time *t-1* to time *t* (kg ha-1)

*Fieldarea* Area of field (ha)

Δ*SOCfarm(t)* Change in SOC from time *t-1* to time *t* for farm (kg)

Once calculated, these estimates may be plotted over time from the historical period (1985 to initial cycle year – 1985 is Holos’ default start year but the user can override this), through the defined cycle (as per user input), and through a future simulation period as defined by the user.

### Carbon emissions from land use

**Concerns:**

* Using the dynamic modelling approach, users can implement multiple management strategies that alter the soil C stock, but the effect of each management practice will be mixed into the effects of others, and practices implemented at a later time may mask the effect of previous choices.
* The use of a single average yield per crop over time allows a (cropping system) comparison approach, but in order to test the applicability of the model using measured values (or assess the real world C change estimate), the model has to be run with annually specific yield values.

**Assumptions:**

* Net CH4 exchange to and from soils is zero
* The past and present farm area is assumed to be constant. (This avoids artificial effects on GHG emissions from changes in farm size)
* Perennial crop area losses are attributed to conversions to annual crops. Perennial conversions to permanent cover do not occur
* Each seeded grassland/permanent cover and perennial crop was converted from annual cropland
* If perennial croplands are present, past perennial crop area is assumed to be zero
* Broken grassland and perennial cropland was converted to annual cropland (therefore, the areas of broken grassland and past perennial cropland can not exceed the present area of annual cropland and fallow)
* Time since management changes refers to the most recent management change
* Intensive tillage – complete burial of residue; vertical mixing of the soil
* Reduced tillage – one or few tillage passes with most residue retained on the surface; horizontal mixing of the soil
* No-till – no tillage at any point in the rotation except at seeding; no mixing of the soil
* Seeding of perennial and grassland, cropping past perennials and breaking grassland is limited to years since 1910

#### Converting carbon to CO2 equivalents

**In order to convert from C to CO2 equivalents (CO2e), C values must be multiplied by 44/12.**

**Eq. 2.1.4‑1**

**Eq. 2.1.4‑2**

#### Monthly Emission Estimate

Yearly soil C values are prorated over 12 months.

**Eq. 2.1.4‑3**

where

*CO2soil(month)* CO2 change for soils (kg CO2 month-1) – by month

*CO2soil* CO2 change for soils (kg CO2 year-1)

*12* Number of months per year

## Intergovernmental Panel on Climate Change (IPCC) Tier 2 Carbon Model

(by R. Kröbel)

**Steady-State Method**

The Tier 2 steady-state method is a three sub-pool steady-state C model that provides an optional alternative method for estimating soil C stock changes in the 0-30 cm layer of mineral soils in cropland remaining cropland.[[6]](#footnote-7) This Tier 2 steady-state method estimates soil C stock changes from combinations of tillage and C-input management activities under conditions defined by the soil texture and the weather.

This is an approach with intermediate complexity between the IPCC (2019) Tier 1 and Tier 3 methods, and is based on a steady-state solution to the three soil organic C sub-pools in the Century ecosystem model (Ogle et al. 2012; Parton et al. 1987; Paustian et al. 1997b). The Tier 2 steady-state method addresses more complexity in soil C dynamics than Tier 1 or Tier 2 using default equations, by subdividing soil organic C into three separate sub-pools with fast (active sub-pool), intermediate (slow sub-pool), and long turnover times (passive sub-pool). The turnover time of C within each sub-pool determines the length of time that C remains in the soil. The Tier 2 steady-state method incorporates spatial and temporal variation in climate, organic C inputs to soils, soil properties and management practices. See **section 2.2.1** (derived from IPCC 2019) for more information about the Tier 2 method.

### Description of the Tier 2 steady state method for estimating mineral soil organic carbon stock changes

The Tier 2 steady-state method is adapted from the Century Ecosystem Model (Parton et al. 1987) and estimates changes in soil organic C for the top 30 cm of the soil profile. In this model, the stock of the soil C sub-pools is initialised by running the model with climate and C input data associated for a period of 5-20 years prior to the start of the inventory (or longer if data are available). A proportion of biomass C (C input to the soil) is transferred to soil litter, and then divided into fraction, β, that goes to metabolic components with the remaining fraction (Cinput - β) going to structural components[[7]](#footnote-8). The structural component is composed of more recalcitrant, ligno-cellulose plant materials. The metabolic component is composed of more readily decomposed organic matter. Decomposition products are transferred according to calculated fractional transfer coefficients (f1 to f8) to and between three soil organic matter sub-pools, active, slow and passive. The active sub-pool is microbial (bacteria and fungi) biomass and associated metabolites with a rapid turnover (months to years), the slow sub-pool has intermediate stability and turnover (decades), and the passive sub-pool is mineral-protected C and microbial decomposition products with long turnover times (centuries). Irrespective of the turnover time the approach is used to estimate the stock of each sub-pool and how they change over time. The total soil organic C stock and stock change is calculated as the sum of the values derived for each sub-pool (Text from IPCC (2019, Box 5.1B)



**Figure 1.** Overview of the IPCC Tier 2 steady state method. Source: IPCC (2019)

Decomposition rates for sub-pools depend on the decay rate constants, temperature effects, and moisture effects. Decomposition of the active and slow sub-pools is also influenced by the soil texture (sand content) and tillage practice. Sub-pools with longer turnover times imply that the C remains in the soil for more years before the organic matter is decomposed and C is respired as CO2 by the soil decomposer community. As decomposition occurs in each sub-pool, some of the decomposing C is transferred to other sub-pools and components (arrows in the diagram) and some of the C is converted into CO2 and lost from the soil (not identified with arrows). The transfer of C to the next sub-pool or component at steady state is determined by the transfer coefficients (f). Higher transfer coefficients imply that more of the C is transferred to the next sub-pool or component rather than converted into CO2. The steady-state solution for this model is discussed further in Paustian et al. (1997) and Ogle et al. (2012).

The land base is stratified as fine as possible to include the spatial variation in climate, soil properties, irrigation, and tillage practices. Each grid cell or region would contain a single combination of climate, soil properties and tillage practices and have an area of land assigned to the unit. Within each grid cell or region, the compiler will determine the C input using country-specific equations, or alternatively a generic equation can be used (Equation 5.0H in IPCC (2019 – see **Eq. 2.2.2‑1** to **Eq. 2.2.2‑5** below). Compilers will also need values for the parameters defining the quality of the C input (lignin and N content) or use generic values available in Tables 5.5B and 5.5C in IPCC (2019) (see **Table 9** and **Table 10**). The type of tillage applied within each grid cell or region will need to be compiled to determine the correct value for tillage parameter. Monthly average temperature, precipitation and potential evapotranspiration is needed for each grid cell or region.

### Estimation of C inputs

#### For annual crops included in the National Inventory Report (NIR) methodology

**Eq. 2.2.2‑1**

Thiagarajan et al. 2018, Eq. 1

where:

*Rag(t)* Harvest ratio = ratio of harvested yield to aboveground residue DM (AGDM(T)) for crop T (Crop(T))

*slope* From **Table 9**

*intercept* From **Table 9**

*Yield* Crop yield (t ha-1, default provided, user override)

*moisturecontent* Crop moisture content (%) (**Table 7**)

**Eq. 2.2.2‑2**

**Eq. 2.2.2‑3**

where:

*AGDM(T)* Aboveground residue DM for crop T (kg DM ha-1)

*AGDMexported(T)* Aboveground residue DM for crop T (kg DM ha-1) that is exported from the field

*Yield(T)* Harvested annual grain yield for crop T (kg DM ha-1)

*RAG(T)* Harvest ratio = ratio of aboveground residues DM (AGDM(T)) to harvested yield for crop T (Crop(T)) (kg DM ha-)-1

*Ss* Percentage of straw returned to soil (user override)

*T* Crop or forage type

**Eq. 2.2.2‑4**

IPCC 2019, Eq. 5.0H

where:

*AGR(T)* Annual total amount of aboveground crop residue for crop T (kg DM yr-)1.

*AGDM(T)* Aboveground residue DM for crop T (kg DM ha-1)

*Area(T)* Total annual area harvested of crop T (ha yr-1)

*FracRenew(T)* Fraction of total area under crop T that is renewed annually (dimensionless)

*FracRemove(T)* Fraction of aboveground residues of crop T removed annually for purposes such as feed, bedding and construction, dimensionless. Survey of experts in country is required to obtain data. If data for FracRemove are not available, assume no removal.

*FracBurnt(T)* Fraction of annual harvested area of crop T burnt, dimensionless. By default, this value is zero

*Cf* Combustion factor (dimensionless) (refer to Chapter 2, Table 2.6 of IPCC 2019)

**Eq. 2.2.2‑5**

IPCC 2019, Eq. 5.0H

where:

*BGR(T)* Annual total amount of belowground crop residue for crop T (kg DM yr-1). **Note:** *BGR(T)* is estimated without the *Ss* parameter in **Eq. 2.2.2‑2** as the amount of belowground biomass produced depends on the amount of aboveground biomass produced and not the amount left in the field

*RS(T)* Shoot to root ratio = ratio of belowground root biomass to aboveground shoot biomass for crop T, (kg DM ha-1) (**Table 9**)

*Area(T)* Total annual area harvested of crop T (ha yr-1)

*FracRenew(T)* Fraction of total area under crop T that is renewed annually (dimensionless). For countries where forages are renewed on average every X years, *FracRenew*(*T*) = 1/X. For annual crops, *FracRenew*(*T*) = 1

#### For crops not in the NIR

**Eq. 2.2.2‑6**

*where*

*Cp* Plant C in agricultural product (kg ha-1)

*Yield* Crop yield (kg DM ha-1, default provided, user override)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)[[8]](#footnote-9)

*Sp* Percentage of product yield returned to soil (user override)

*For annual crops, perennial crops, and fodder corn.*

**Eq. 2.2.2‑7**

**Eq. 2.2.2‑8**

*For root crops.*

**Eq. 2.2.2‑9**

**Eq. 2.2.2‑10**

where

*Cag* Aboveground residue C input (kg ha-1)

*CptoSoil* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*Cbg* Belowground residue C input (kg ha-1)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

##### For annual crops not in the NIR

Follow methodology in section 2.1.2.2

##### Silage crops

Follow methodology in section 2.1.2.3

##### Cover crops

Follow methodology in section 2.1.2.4

##### Root crops

Follow methodology in section 2.1.2.5

##### Perennials

Follow methodology in section 2.1.2.6

##### Rangeland

Follow methodology in section 2.1.2.7

##### Fallow

Follow methodology in section 2.1.2.8

##### Manure

Follow methodology in section 2.1.2.8

##### Total input

**Eq. 2.2.2‑11**

IPCC 2019, Eq. 5.0H

where:

*AGR(T)* Annual total amount of aboveground crop residue for crop T (kg DM yr-1)

*CAG(T)* C content of aboveground residues for crop T (kg C kg-1 DM) (Default: 0.42 kg C kg-1 DM)

*BGR(T)* Annual total amount of belowground crop residue for crop T (kg DM yr-1)

*CBG(T)* C content of belowground residues for crop T (kg C kg-1 DM), (Default: 0.42 kg C kg-1 DM)

*CM(T)* C in livestock manure applied to crop T (kg C) (**Eq. 2.1.3‑3**)

*Cinput* Summation of C inputs (t C ha-1)

### Calculate the initial stocks of the active, slow and passive SOC sub-pools

The initial stocks are calculated based on the climatic, soil texture, management and C input data for a run-in period of 5 to 20 years (more years may be used if data are available).

#### Calculate the average annual values of *tfac* and *wfac* for the run-in period

**Eq. 2.2.3‑1**

IPCC 2019, Eq. 5.0E

**Eq. 2.2.3‑2**

IPCC 2019, Eq. 5.0E

where:

*tfac* Annual average air temperature effect on decomposition (dimensionless)

*Ti* Monthly average air temperature effect on decomposition (dimensionless) (*i* = 1, 2, …, 12)

*tmax* Maximum monthly air temperature for decomposition (°C) (see **Table 8**)

*tempi* Monthly average air temperature (*i* = 1, 2, …, 12) (°C)

*topt* Optimum air temperature for decomposition (°C) (see **Table 8**)

**NOTE: When the monthly average air temperature is greater than 45 °C (i.e., the maximum average air temperature) set to *Ti* 0**

**Eq. 2.2.3‑3**

IPCC 2019, Eq. 5.0F

where:

*mappet i* Ratio of total precipitation to total potential evapotranspiration (dimensionless) for month *i* (i = 1, 2, …12)

*precip i* Total precipitation for month *i* (mm)

*PET i* Total potential evapotranspiration for month *i* (mm)

**Eq. 2.2.3‑4**

IPCC 2019, Eq. 5.0F

where:

*wi* Monthly water effect on decomposition (dimensionless)

*ws* Modifier for *mappeti* (dimensionless) (**Table 8**)

**Eq. 2.2.3‑5**

IPCC 2019, Eq. 5.0F

where:

*wfac* Annual water effect on decomposition (dimensionless)

**NOTE: If *mappet i* is >1.25, then set the value of *mappet i* for the month to 1.25 for non-irrigated system (i.e., *mappet i* does not exceed 1.25). Set *wi* for months with irrigation to 0.775.**

#### Calculate the C input to the active sub-pool (α) for the run-in period using the following data:

**Eq. 2.2.3‑6**

IPCC 2019, Eq. 5.0C

where:

*f4* Fraction of active sub-pool decay products transferred to the Slow sub-pool (proportion)

*f5* Fraction of active sub-pool decay products transferred to the passive sub-pool (proportion) (**Table 8**)

*sand* Fraction of 0-30 cm soil mass that is sand (0.050 – 2mm particles) (proportion)

**Eq. 2.2.3‑7**

IPCC 2019, Eq. 5.0G

where:

*β* C input to the metabolic dead organic matter C component (t C ha-1 year-1)

*Cinput* Total C input (t C ha-1 year-1)

LC Lignin content of the C input (proportion) (**Table 9** for default values, otherwise compile country-specific values)

NC N fraction of the C input (proportion) (**Table 9** for default values, otherwise compile country-specific values)

**Eq. 2.2.3‑8**

IPCC 2019, Eq. 5.0G

where:

*α* C input to the active soil C sub-pool (t C ha-1)

*f1* Fraction of metabolic dead organic matter decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f2* Fraction of structural dead organic matter decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f3* Fraction of structural dead organic matter decay products transferred to the slow sub-pool (proportion) (**Table 8**)

*f6* Fraction of slow sub-pool decay products transferred to the passive sub-pool (proportion) (**Table 8**)

*f7* Fraction of slow sub-pool decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f8* Fraction of passive sub-pool decay products transferred to the active sub-pool (proportion) (**Table 8**)

**Table 8** provides the default parameters, minimum and maximum values for parameters, and their associated standard deviation. The probability distribution functions for the parameters should be constructed as truncated normal distributions, in which parameter values lower than the minimum value are constrained the minimum value, and parameter values greater than the maximum values are constrained to the maximum value. Uncorrelated draws from the probability distribution functions of the parameters can be made using the data in this table, but more robust estimates of uncertainty can be made using a truncated joint probability distribution with the parameter covariance matrix found in IPCC (2019), Annex 2A.3.

#### Calculate *ka*, *ks* and *kp*

The parameters *ka* (the decay rate for the active SOC sub-pool), *ks* (the decay rate for the slow SOC sub-pool), and *kp* (the decay rate for the passive SOC sub-pool) are calculated using the average values of *tfac* and *wfac* calculated in **Eq. 2.2.3‑2** and **Eq. 2.2.3‑5**; the values of *kfaca*, *kfacs*, and *kfacp*; the appropriate tillage factor (*tillfac*) from **Table 8**; and the sand content of the 0-30 cm soil layer (*sand*).

**Eq. 2.2.3‑9**

IPCC 2019, Eq. 5.0B

where:

*ka* Decay rate for active SOC sub-pool (year-1) (**value cannot be higher than 1**)

*kfac a* Decay rate constant under optimal conditions for decomposition of the active SOC sub-pool (year-1) (see**Table 8**)

*tfac* Temperature effect on decomposition (dimensionless) (see **Eq. 2.2.3‑2**)

*wfac* Water effect on decomposition (dimensionless) (see **Eq. 2.2.3‑5**)

*tillfac* Tillage disturbance modifier on decay rate for active and slow sub-pools (dimensionless) (see **Table 8**)

*sand* Fraction of 0-30 cm soil mass that is sand (0.050 – 2 mm particles) (dimensionless)

**Eq. 2.2.3‑10**

IPCC 2019, Eq. 5.0C

where:

*ks* Decay rate for slow SOC sub-pool (year-1) (**value cannot be higher than 1**)

*kfacs* Decay rate constant under optimal condition for decomposition of the slow C sub-pool (year-1) (see **Table 8**)

*tfac* Temperature effect on decomposition (dimensionless) (see **Eq. 2.2.3‑2**)

*wfac* Water effect on decomposition (dimensionless) (see **Eq. 2.2.3‑5**)

*tillfac* Tillage disturbance modifier on decay rate for active and slow sub-pools (dimensionless) (see **Table 8**)

**Eq. 2.2.3‑11**

IPCC 2019, Eq. 5.0D

where:

*kp* Decay rate for passive SOC sub-pool (year-1) (**value cannot be higher than 1**)

*kfacp* Decay rate constant under optimal conditions for decomposition of the slow C sub-pool (year-1) (see **Table 8**)

*tfac* Temperature effect on decomposition (dimensionless) (see **Eq. 2.2.3‑2**)

*wfac* Water effect on decomposition (dimensionless) (see **Eq. 2.2.3‑5**)

#### Calculate the values for *Activey*, *Slowy* and *Passivey* for the run-in period

The values for the active (*Activey)*, slow (*Slowy*) and passive (*Passivey*) sub-pools become the initial SOC stocks for each of these SOC sub-pools at the start of the inventory period.

**Eq. 2.2.3‑12**

IPCC 2019, Eq. 5.0B

where:

*Activey\** Steady state active sub-pool SOC stock given conditions in year y (t C ha-1)

*ka* Decay rate for active SOC sub-pool (year-1) (**value cannot be higher than 1**)

*α* C input to the active SOC sub-pool (t C ha-1 year-1) (**Eq. 2.2.3‑8**)

**Eq. 2.2.3‑13**

IPCC 2019, Eq. 5.0B

where:

*Activey* Active sub-pool SOC stock in year y (t C ha-1)

*Activey-1* Active sub-pool SOC stock in previous year (t C ha-1)

**Eq. 2.2.3‑14**

IPCC 2019, Eq. 5.0C

where:

*Slowy* Slow sub-pool SOC stock in y (t C ha-1)

*Cinput* Total C input (t C ha-1 year-1)

*LC* Lignin content of C input (proportion) (see **Table 9**) for default values, otherwise compile country-specific values)

*f3* Fraction of structural component decay products transferred to the slow sub-pool (proportion) (see **Table 8**)

*Activey\** Steady state active sub-pool SOC stock given conditions in year y (t C ha-1)

*ka* Decay rate for active C sub-pool in the soil (year-1)

*f4* Fraction of active sub-pool decay products transferred to the slow sub-pool (proportion) (see **Eq. 2.2.3‑6**)

*ks* Decay rate for slow SOC sub-pool (year-1) (**value cannot be higher than 1**)

**Eq. 2.2.3‑15**

IPCC 2019, Eq. 5.0C

where:

*Slowy-1* Slow sub-pool SOC stock in previous year (t C ha-1)

*Slowy\** Steady state slow sub-pool SOC stock given conditions in year y (t C ha-1)

**Eq. 2.2.3‑16**

IPCC 2019, Eq. 5.0D

where:

*Passivey* Passive sub-pool SOC stock in year y (t C ha-1)

*kp* Decay rate for passive SOC sub-pool (year-1) (**value cannot be higher than 1**)

*Activey\** Steady state active sub-pool SOC stock given conditions in year y (t C ha-1)

*ka* Decay rate for active C sub-pool in the soil (year-1)

*Slowy\** Steady state slow sub-pool SOC stock given conditions in year y (t C ha-1)

*ks* Decay rate for slow SOC sub-pool (year-1)

*f5* Fraction of active sub-pool decay products transferred to the slow sub-pool (proportion) (see **Table 8**)

*f6* Fraction of slow sub-pool decay products transferred to the passive sub-pool (proportion) (see **Table 8**)

**Eq. 2.2.3‑17**

IPCC 2019, Eq. 5.0D

where:

*Passivey-1* Passive sub-pool SOC stock in previous year (t C ha-1)

*Passivey\** Steady state passive sub-pool SOC given conditions in year y (t C ha-1)

### Calculate C inputs to the active sub-pool for each year of the inventory period

#### Calculate the C input to the metabolic dead organic matter component (β)

The C input to the metabolic dead organic matter C component (β) is calculated using **Eq. 2.2.3‑7**.

#### Calculate the C input to the active soil carbon sub-pool (α)

The C input to the active soil C sub-pool (α) is calculated using **Eq. 2.2.3‑8**.

**Repeat steps 2.2.4.1 and 2.2.4.2 for all other years in the inventory period to derive annual values for α and β**

### Calculate the water effect on decomposition

#### Monthly water effect on decomposition (*wi*)

The parameters *mappeti* (ratio of total precipitation to total potential evapotranspiration for month *i* and *wi* (monthly water effect on decomposition) are estimated using **Eq. 2.2.3‑3** and **Eq. 2.2.3‑4**.

For each month in a year, calculate the ratio of total precipitation to total potential evapotranspiration. If the ratio is ≤1.25 then set the value of *mappeti* for the month to the estimated ratio; if the ratio is >1.25 then set the value of *mappeti* for the month to 1.25; set *wi* for months with irrigation to 0.775.

#### Calculate water effect on decomposition for each month (*wi*) in a year.

For land area under irrigation management, set the water effect on decomposition for the month (*wi* ) to 0.775.

#### Annual water effect on decomposition (*w fac*)

The annual water effect on decomposition is calculated using **Eq. 2.2.3‑5**.

**Repeat steps 2.2.5.1 and 2.2.5.3 to to calculate the water effect (*w fac*) on decomposition for all years in the inventory period.**

### Calculate the temperature effect on decomposition

#### Monthly temperature effect on decomposition (*Ti*)

For each month in the year, calculate the temperature effect on decomposition (*T i*) is calculated using **Eq. 2.2.3‑1** and the values for maximum monthly temperature for decomposition (*t max*), optimum temperature for decomposition (*t opt*) and the monthly average temperature (*temp i*).

**Note: If the monthly average air temperature is ≤45 °C, use the calculated value of *Ti*;**

**If the monthly average temperature is >45 °C, set *Ti* equal to 0.**

#### Annual temperature effect on decomposition (*Tfac*)

The annual temperature effect on decomposition is calculated using **Eq. 2.2.3‑2**.

**Repeat steps 2.2.6.1 to 2.2.6.2 to calculate the annual temperature effect on decomposition for all years in the inventory.**

### Calculate the size of the passive C Sub-pool

#### Decay rate for the passive SOC sub-pool in the soil *(k p*).

To calculate the decay rate for the passive SOC soil sub-pool, use **Eq. 2.2.3‑11**.

#### Steady state stock for the passive sub-pool SOC stock (*Passive y*\*)

To calculate Passivey\*, use **Eq. 2.2.3‑16**

#### Passive sub-pool SOC stock (*Passivey*)

Passivey is calculated by determining the additional increase or decrease in SOC from the previous year in the inventory. This is estimated using **Eq. 2.2.3‑17**.

**Note: If the estimated *kp* value is above 1, then set the value of *kp* to 1 in the equation for calculating *Passivey*.**

**Repeat steps 2.2.7.1 to 2.2.7.3 to calculate the passive SOC stocks for all years in the inventory.**

### Calculate the size of the slow SOC Sub-pool

#### Decay rate for the slow SOC sub-pool in the soil (*ks*)

*Ks* is estimated using **Eq. 2.2.3‑10**.

#### Steady state stock for the slow SOC sub-pool (*Slowy*\*)

*Slowy\** is estimated using **Eq. 2.2.3‑14**.

#### Slow sub-pool SOC (*Slowy*)

The slow sub-pool SOC stock (*Slowy*) is estimated by determining the additional increase or decrease in SOC from the previous year in the inventory using **Eq. 2.2.3‑15**.

**Note: if the estimated *ks* value is above 1, then set the value of *ks* to 1 in the equation for calculating *Slowy*.**

**Repeat steps 2.2.8.1 and 2.2.8.3 to calculate the slow SOC sub-pool stocks for all years in the inventory.**

### Calculate the size of the active SOC sub-pool

#### Decay rate for the active SOC sub-pool in the soil (*ka*)

To estimate *Ka* use **Eq. 2.2.3‑9**.

#### Steady state stock for the active SOC sub-pool (*Activey*\*)

To calculate *Activey\**, use **Eq. 2.2.3‑12**.

#### Active sub-pool SOC stock (*Active y*)

The active SOC stock (*Activey*) is estimated by determining the additional increase or decrease in SOC from the previous year in the inventory using **Eq. 2.2.3‑13**.

**Note: if the estimated *ka* value is above 1, then set the value of *ka* to 1 in the equation for calculating *Active y*.**

**Repeat steps 2.2.9.1 and 2.2.9.3 to calculate the active SOC sub-pool stocks for all years in the inventory.**

### Calculate the total annual SOC stock change

#### SOC stock (*SOCy*) for each grid cell or region

**If the user supplied a custom soil C content, the run-up period will be run using average default year (10yr average ahead of the start year) and used to calculate the fractions of the pools from the pools after 5 yrs (default that can be adjusted):**

**Eq. 2.2.10‑1**

**Eq. 2.2.10‑2**

**Eq. 2.2.10‑3**

where:

*SOCuser-supplied* SOC stock as supplied by the user (t C ha-1)

*Activeyi* Active sub-pool SOC stock in year *y* for grid cell or region (t C ha-1)

*Slowyi* Slow sub-pool SOC stock in year *y* for grid cell or region (t C ha-1)

*Passiveyi* Passive sub-pool SOC stock in year *y* for grid cell or region (t C ha-1)

*FractionActive* Pool fraction as determined by the run with default input for the location (dimensionless)

*FractionSlow* Pool fraction as determined by the run with default input for the location (dimensionless)

*FractionPassive* Pool fraction as determined by the run with default input for the location (dimensionless)

Use **Eq. 2.2.10‑4** to estimate *SOCyi* for each grid cell or region by summing the SOC in the active (*Activey*), slow (*Slowy*) and passive (*Passivey*) sub-pools.

**Eq. 2.2.10‑4**

IPCC 2019, Eq. 5.0A

where:

*SOCyi* SOC stock at the end of the current year y for grid cell or region (t C ha-1)

*Activeyi* Active sub-pool SOC stock in year *y* for grid cell or region (t C ha-1) (**Eq. 2.2.2‑23**)

*Slowyi* Slow sub-pool SOC stock in year *y* for grid cell or region (t C ha-1) (**Eq. 2.2.2‑25**)

*Passiveyi* Passive sub-pool SOC stock in year *y* for grid cell or region (t C ha-1) (**Eq. 2.2.2‑27**)

#### Stock change factor (𝐹𝑆𝑂𝐶𝑖) for each grid cell or region

**Eq. 2.2.10‑5**

IPCC 2019, Eq. 5.0A

where:

*FSOCi* Annual stock change factor for mineral soils in grid cell or region *i* (t C ha-1)

*SOCyi* SOC stock at the end of the current year y for grid cell or region (t C ha-1)

*SOC(y-1)i* SOC stock at the end of the previous year for grid cell or region (t C ha-1)

#### Total change in SOC stock (*ΔCMineral*)

The total change in the SOC stock us calculated by multiplying the stock change factor (𝐹𝑆𝑂𝐶𝑖) by the area of the grid cell or region *i* (*A*), and summing the changes across all land included in the Tier 2 steady-state method.

**Eq. 2.2.10‑6**

IPCC 2019, Eq. 5.0A

where:

*ΔCmineral* Annual SOC stock change factor for mineral soil, summed across all *i* grid cells or regions (t mineral C)

*FSOCi* Annual stock change factor for mineral soils in grid cell or region *i* (t C ha-1)

*Ai* Area of grid cell or region (ha)

## Shelterbelt and lineal tree planting

(by J. Moore, B.Y. Amichev and R. Kröbel)

The new shelterbelt component was designed in collaboration with the Agricultural Greenhouse Gas Program (AGGP) shelterbelt projects led by Profs. K. Van Rees and C. Laroque, represented by B.Y. Amichev, and their immense measurement work throughout the province of Saskatchewan, which has dprovided the platform for this component and the estimates for other provinces. For the calculations and the models outputs, the following underlying rules are present and unchangeable:

* Ecodistrict-specific lookup tables are used for respective SLC-polygons in Saskatchewan province.
* An area-weighted average was calculated for each plant hardiness zone that overlaps with ecodistricts withavailable lookup table values, and that average is used when calculating tree C stocks in matching plant hardiness zones outside of Saskatchewan (Plant Hardiness Zones 2A – 4B).
* Plant hardiness zones outside the range 2A – 4B cannot be modelled until more data become available.
* Species selection is limited (at this time) to White Spruce, Scots Pine, Hybrid Poplar, Manitoba Maple, Green Ash, and Caragana.
* For all other species, the option of an average deciduous tree (average of Manitoba Maple and Green Ash) or average coniferous tree (average of White Spruce and Scots Pine) is provided.
* All lookup table values are limited to a tree age of 60 as no supporting data were available to provide information on the magnitude of change beyond that age. If trees are older than 60 years of age, the 60-yr C stock value from the lookup tables is used as a conservative approximate value.
* Trees within one row must have the same planting year. For replanted trees or for replacement trees (due to tree damage or death from wind, insects, or other animals), additional rows need to be added.
* Multiple species can be input in one row, but they will be calculated as individual rows, and summed together to estimate the entire row’s C stocks.
* Tree mortality is calculated across a linear planting (i.e. row within a shelterbelt, potentially with multiple species), from the planting date to the year of observation. For mortality levels of 0% (i.e., no trees are dead), 15%, 30%, 50%, and 100% (i.e., all trees are dead - C values are 0 Mg/km), respective growth rates (or lack thereof) will be looked up.
* It is assumed that if trees die, they do so in the first year. Outputs are limited to the number of trees staying alive, and respective mortality specific growth rates will be assumed for the entire growth period.
* The user can specify tree losses in the detailed inputs if they have such information, but the mortality specific growth rates will not change.

### Lookup of factors and values from the Shelterbelt Table

**Values are looked up according to the user specified mortality rate in the shelterbelt and averaged from the available mortality specific values (0, 15, 30, 50 and 100% mortality) in the growth database.**

**Eq. 2.3.1‑1**

where

*Mortality* Percent mortality of an entire linear planting (i.e. row).

Number of trees originally planted into the linear planting

Number of trees alive for all species in a linear planting

For custom mortality values that fall between those levels in the lookup tables, Mortality Low and Mortality High are used. For example, for a custom mortality of 10%, the Mortality Low lookup is 0% and the High is 15%. Mortality Low and Mortality High are defined this way to avoid potential problems associated with the rounding of values close to the cut-off. Therefore, the cut-off value closest to the mortality value is present either in MortalityLow or MortalityHigh, regardless of the rounding procedure of an individual computer.

**Eq. 2.3.1‑2**

where

*MortalityLow* Percent mortality used for looking up values in **Table 12**. Represents the lesser value used in linear interpolation.

**Eq. 2.3.1‑3**

where

*MortalityHigh* Percent mortality used for looking up values in **Table 12**. Represents the greater value used in linear interpolation.

**Eq. 2.3.1‑4**

where

*AboveGroundBiomasstree* Aboveground biomass per tree (kg tree-1)

*Biomasslookup* Aboveground biomass of an average (ideal) tree recorded for an area of similar geographical location (Saskatchewan) or ecological condition (plant hardiness zone outside SK) (kg tree-1)

*Rootslookup* Root biomass of an average (ideal) tree (kg tree-1); this value already includes the Finerootslookup

Furthermore, the determined mortality and user provided age of the shelterbelt are used to lookup the values for Dead Organic Matter (DOMlookup) (Mg C km-1 yr-1) and Total Living Biomass Carbon (TLBClookup) (Mg C km-1 yr-1) from the C database.

### Calculating the current tree biomass – conifers and deciduous trees

**Eq. 2.3.2‑1**

Amichev et al. 2017

where

*AboveGroundBiomasstree* Aboveground biomass per tree (kg tree-1)

*a* Coefficient a (**Table 11**)

*b* Coefficient b (**Table 11**)

*average circumference* Average of the following property over one or more trees: cumulative tree stem circumference (cm) at 1.3 m height along the individual stem (breast height) (outside bark)

**Note:** AboveGroundBiomasstree is averaged for Average Conifer (Scots Pine and White Spruce) and Average Deciduous (Green Ash and Manitoba Maple).

**Eq. 2.3.2‑2**

where

*diameter* Diameter of a circle (cm)

*circumference* Circumference of a circle (cm)

**Note:** If multiple stems are present per single tree, a cumulative basal area (BA, cm2) is estimated first by using the circumferences of all stems (diameteri; i=1,2,…nth stem), and then, a cumulative circumference is estimated. Calculating the area of each stem from their circumference, and then calculating a circumference from the combined area is simplified to the following:

**Eq. 2.3.2‑3**

where

*tree circumference* Cumulative tree stem circumference (cm) at 1.3m height along the individual stem (breast height) (outside bark).

*circumferencei* Circumference at breast height of anindividual stem (cm)

**Eq. 2.3.2‑4**

where

n Number of trees sampled

**Eq. 2.3.2‑5**

where

*Biomasstree* Total tree biomass (kg tree-1); (total biomass = aboveground + belowground)

*AboveGroundBiomasstree* Aboveground biomass per tree (kg C tree-1)

*AboveGroundBiomassratio* Fraction of aboveground over total biomass (total biomass = aboveground + belowground), derived from **Table 12,** specific to the **user-provided age and mortality** of the shelterbelt (%/100)

### Total (current) living biomass (TLB) in the Shelterbelt (corrected to a length of 1 km)

**Eq. 2.3.3‑1**

where

*tree count* Number of live trees of a particular species/taxon within a given linear planting.

*Mortality* Percent dead trees over planted trees

*row length* Length of a given linear planting.

*tree spacing* Space between one tree of a given kind and the next within a given linear planting.

**Eq. 2.3.3‑2**

where

*Biomasstreetype* Biomassof trees of a particular kind within a linear planting (kg planting-1)

**Eq. 2.3.3‑3**

where

*TLBtreetype* Total tree biomass per standard length (1 km) linear planting (kg km-1)

**Eq. 2.3.3‑4**

where

*TLCtreetype* Total C stocks in the living biomass per standard length linear planting (kg C km-1)

**Eq. 2.3.3‑5**

where

*TLBCtreetype* Total C stocks per average (ideal) tree recorded for an area of similar geographical location (Saskatchewan) or ecological condition (plant hardiness zone outside SK) (kg C km-1)

*RealGrowthratio* Ratio of user specified over average (ideal) tree growth

**The established ratio of the user-defined over the recorded average (ideal) tree growth allows back- and forward estimation of the C in the living tree biomass.**

**Eq. 2.3.3‑6**

**Finally, the different trees assigned to the shelterbelt are summed up in a C in the living shelterbelt biomass estimate.**

**Eq. 2.3.3‑7**

where

*TLCshelterbelt* Total C stocks in the living biomass of the user-defined shelterbelt (kg C shelterbelt-1)

Holos V4 will use the following constant values:

*Carbonconcentration(trees)* 0.5 kg kg-1 (Kurz et al. 2009)

*Standard length* 1 km

### Total carbon in shelterbelt / lineal tree plantings

**If DOMlookup <0**

**Eq. 2.3.4‑1**

**If DOMlookup >=0**

**Eq. 2.3.4‑2**

where

*DOMfarm* Dead organic matter change in the soil (kg C km‑1 yr-1)

**Eq. 2.3.4‑3**

where

*TEC*Total C gain in the current year in the user-defined shelterbelt (kg C shelterbelt‑1 yr-1)

**Eq. 2.3.4‑4**

where

*TEC*Total C accumulation in all years in the user-defined shelterbelt (kg C shelterbelt‑1)

**Eq. 2.3.4‑5**

where

*Total\_Cshelterbelt* Total C gain in the current year in the user-defined shelterbelt (kg C shelterbelt‑1 yr-1)

**Eq. 2.3.4‑6**

### Convert C to CO2 emissions

**Eq. 2.3.5‑1**

**Eq. 2.3.5‑2**

where

*Total\_CO2 shelterbelt(accumulate)* Total CO2 sequestration in tree plantings/shelterbelt (kg CO2 shelterbelt-1)

*Total\_Cshelterbelt(accumulate)* Total C accumulation in tree plantings/shelterbelt (kg C shelterbelt-1)

*Total\_CO2 shelterbelt(t)* Annual CO2 sequestration from tree plantings/shelterbelt (kg CO2 shelterbelt-1 yr-1)

*Total\_Cshelterbelt(t)* Annual C accumulation in tree plantings/shelterbelt (kg C shelterbelt-1 yr-1)

44/12 Conversion from C to CO2

## Water budget model

There is a simplified water budgeting routine within the re-crop calculation for the ICBM model (**section 2.1.1.1.2**). The Holos team has developed a Canada specific water budget model (Martel et al. 2021) that is more detailed, but this has not yet been incorporated into the Holos model. Our goal is to add the new water budget model in the next iteration of Holos, at which point this technical document will be re-published or updated accordingly.

### Evapotranspiration

* To be added

### Run-off and Infiltration

* To be added

### Water movement

* To be added

### Root growth and water extraction

* To be added

## Nitrous oxide emission factor calculation (IPCC Canada Tier 2)

Management factors are input for each year. Emissions are calculated yearly and pro-rated for monthly emission estimates. Organic soils are currently not considered.

C:\Users\Ke Gao Long\Pictures\N2O EF.tif

**Figure 2.** Schematic representation of the Canadian N2O emission factor calculation (derived from Liang et al., 2020)

**Assumptions:**

* All manure is land-applied yearly and emissions are allotted to the farm of manure origin.
* Crop residue emissions are allotted to the farm of residue origin.
* Emissions are calculated based on the specified farm soil texture.
* N2O emissions from decay of residues containing biologically-fixed N are included.
* Emissions from mineralized N are distributed equally among the cropped land area.
* **The texture, where not specified in Table 13, has no effect (RF=1)**
* **For all perennials systems, N source and tillage have no effect (RF=1)**
* **No till and reduced tillage are combined into conservation tillage**
* **Irrigation iterates the base EF directly, RF adjustments apply regardless**

### Base emission factor

**Eq. 2.5.1‑1**

**Eq. 2.5.1‑2**

Liang et al. 2020

where

*EF\_CTi* Ecodistrict-level emission factor [kg N2O-N (kg N)-1]

*Pi* Annual growing season precipitation (May – October), in ecodistrict “i” (mm)

*PE* Growing season potential evapotranspiration, by ecodistrict (May – October)

***P* and *PE* values are obtained from CanSIS using the average of 1980 - 2010 data (Marshall et al., 1999, Newlands et al., 2011).**

### Emission factor adjustment due to position in landscape/topography

**For humid environments (P/PE >1)**

**Eq. 2.5.2‑1**

**For dry environments (P/PE <= 1)**, the fraction of low-laying land and depressions is calculated with the actual *PE* (EF\_CTi,P<PE), and the remainder of the land with the standard EF (EF\_CTi,P>PE).

**Eq. 2.5.2‑2**

**For irrigated sites (only on sites where P < PE, and the assumption is that the irrigation amount is equal to PE-P, thus making P = PE)**

**Eq. 2.5.2‑3**

Liang et al.2020

where

*EF\_Topoi*N2O emission factor adjusted due to position in landscape and moisture regime (kg N2O-N)

*FR\_Topoi* Fraction of land occupied by lower portions of landscape (from Rochette *et al.* 2008)

### Emission factor adjustment due to soil texture

**Equation 2.5.1-6 is not currently in use (it would require allowing to specifiy multiple textures within one field).**

**Eq. 2.5.3‑1**

**Eq. 2.5.3‑2**

Liang et al. 2020; Pelster et al. 2022

where

*RF\_TXi* Weighted modifier which provides a correction of the EF\_Topo in ecodistrict ‘‘i’’ based on the soil texture

*RF\_TXj* Soil texture modifier (with ‘*j’* beingcoarse, medium or fine), provided in **Table 13**

*FR\_TXi,j* Fraction of different textured soils in ecodistric ‘i’

*EF\_Basei* A function of the three factors that create a base ecodistrict specific value that accounts for the climatic, topographic and edaphic characteristics of the spatial unit for lands

*1/0.634* Fraction of growing season emissions of total annual emissions (Pelster et al. 2022, in prep.)

### Emission factor adjustment due to N source, tillage, cropping system and moisture management system

**Eq. 2.5.4‑1**

Based on Liang et al. 2020

where

*EFi,k,l,m,n* Emission factor considering the impact of the N source on the cropping system and site dependent factors associated with rainfall, topography, soil texture, N source type, tillage, cropping sytem and moisture managment (kg N2O-N kg-1 N) for ecodistrict ‘‘i’’.

*i* Ecodistrict identifier

*k* N source modifier RF\_NSk (SN = Synthetic Nitrogen; ON = Organic Nitrogen; CRN = Crop Residue Nitrogen)

*l* Tillage modifier RF\_Till (Conservation or Conventional Tillage)

*RF\_AM* Reduction factor based on application method (**Table 13**), **only applicable to calculations of EF specific for SN**

### Calculating crop fertilizer N inputs

**Calculate the input for each crop independently. Holos calculates a default fertilization rate adjusted for the user-provided crop yield, but the user is expected to override the fertilization rate with actual application rates.**

Fertilizer input calculations should be completed for all fertilized crop types, including annual crops, perennial forages and improved grassland/pasture (improved grassland/pasture is pasture that is fertilized and/or irrigated).

**When user supplies fertilizer input information:**

**Eq. 2.5.5‑1**

**Eq. 2.5.5‑2**

**Eq. 2.5.5‑3**

**Eq. 2.5.5‑4**

where

*Nfert\_applied* Amount of N applied to a field *n* (kg N ha-1)

*N(product)* Amount of N fertilizer product applied (kg ha-1)

*P(product)* Amount of N fertilizer product applied (kg ha-1)

*K(product)* Amount of N fertilizer product applied (kg ha-1)

*Ncontent(product)* Amount of N contained in a product (kg N kg product-1), see **Table 48**

**Default fertilizer calculation when no information is supplied by user (fertilizer amounts cannot be smaller than 0 kg N ha-1):**

**For non-leguminous crops:**

**Eq. 2.5.5‑5**

**For legumes:**

**Eq.** **2.5.5‑6**

**Eq. 2.5.5‑7**

where

Fertefficiency Fertilizer use efficiency (fraction)

SoiltestN

GrainNTotal N content of all grain (kg N ha-1), calculated using **Eq. 2.5.6‑1**

*StrawN* N content of all straw (kg N ha-1), calculated using **Eq. 2.5.6‑3**

*RootN* N content of all root (kg N ha-1), calculated using **Eq. 2.5.6‑4**

*ExudateN* N content of all root exudates (kg N ha-1), calculated using **Eq. 2.5.6‑5**

*Nfixation* Fraction of plant N requirement that is fixated (fraction)

*Nfert\_applied(field n)* Amount of N applied (kg N ha-1) to field *n*

*Ncontent(product)* Amount of N contained in a synthetic fertilizer product (kg N kg product-1), see **Table 48**

*N(product)* Amount of N fertilizer product applied (kg product ha-1)

*N\_fert\_deposit(field n)* N deposition on field *n* (kg N ha-1) (user defined)

**Note:** the default fertilizer types are urea (for annual crops) and UAN (for silage) – these can be overridden by the user

Holos V4 will use the following constant values:

*Fertefficiency* 0.75 (user can override)

*Nfixation*0.7 (fraction – H. Janzen)

*N\_fert\_deposit(field n)* 5 kg N ha-1 (Janzen et al., 2003)

### Crop residue N inputs

Calculate the input for each crop independently. Residue input calculations should be completed for all crop types, including annual crops and perennial forages.

**Eq. 2.5.6‑1**

**Eq. 2.5.6‑2**

**Eq. 2.5.6‑3**

**Eq. 2.5.6‑4**

**Eq. 2.5.6‑5**

where

*CptoSoil* Carbon input from product (kg ha-1)

*Cs* Carbon input from straw (kg ha-1)

*Cr* Carbon input from roots (kg ha-1)

*Ce* Carbon input from extra-root material (kg ha-1)

*NP* N concentration in the product (kg kg-1) (Table 10)

*NS* N concentration in the straw (kg kg-1) (Table 10)

*Nr* N concentration in the roots (kg kg-1) (Table 10)

*Ne* N concentration in the extra root material (kg kg-1) (until known from literature, the same N concentration used for roots will be utilized)

#### Aboveground residue N

**Eq. 2.5.6‑6**

where

*AGresidue\_N* Aboveground residue N (kg N ha-1)

*AGresidueN(crop)* Aboveground residue N (kg N ha-1)

*GrainN* Nitrogen content of the grain returned to the soil (kg N ha-1)

*StrawN* Nitrogen content of the straw returned to the soil (kg N ha-1)

#### Belowground residue

Equation **Eq. 2.5.2‑19** should be used for all annual crop types while equation  **Eq. 2.5.2‑20** is used for perennial forages.

For annual crops:

**Eq. 2.5.6‑7**

For perennial forages (hay):

**Eq. 2.5.6‑8**

where

*BGresidue N(crop)* Belowground residue N (kg N ha-1)

*RootN* Nitrogen content of the root returned to the soil (kg N ha-1)

*ExudateN* Nitrogen content of the exudates returned to the soil (kg N ha-1)

*Sr* Root turnover fraction

#### Total residue

**Eq. 2.5.6‑9**

where

*NCropResidues* N inputs from crop residue returned to soil (kg N)

*area* Area of crop (ha)

## Multi-year estimation of nitrous oxide (adapted Liang et al. 2020 with N carryover) for ICBM

(by R. Kröbel, A. McPherson and S.J. Pogue)

Holos utilizes emission factor calculations from the single year model described above, but with specifications for field and year

A screenshot of a computer screen

Description automatically generated

Pools of mineral N and microbial N carry over from year to year, thus, at the start of the year *NmineralN(t,field n)* takes the value of *NmineralN(t-1,field n)* and *NmicrobeN(t,field n)* takes the value of *NmicrobeN(t-1,field n)*.

*NmicrobeN(t=0,field n)* starts with 25kg N.

### Synthetic and organic N fertilizer applications (not manure)

For N synthetic fertilizer applications inputs for each field are calculated independently**. Results are provided by field and/or crop.**

Fertilizer input calculations should be completed for all fertilized crop types, including annual crops, perennial forages and improved grassland/pasture (improved grassland/pasture is pasture that is fertilized and/or irrigated).

**Eq. 2.6.1‑1**

**Eq. 2.6.1‑2**

where

*NSN(field n)* N inputs from synthetic fertilizer (kg N ha-1) applied to field *n* (provided through **Eq. 2.5.2‑5**, if not specified otherwise by the user)

*N\_fert\_applied(field n)* N fertilizer applied to field *n* (kg ha-1)

*N\_fert\_deposit(field n)* N deposition on field *n* (kg ha-1) (user defined)

Holos V4 will use the following constant values:

*N\_fert\_deposit(field n)* 5 kg N ha-1 (Janzen et al., 2003)

Organic fertilizer applications (user-defined only until default options are added to the model) are treated as different from synthetic fertilizers:

**Eq. 2.6.1‑3**

where

*NON(field n)* N inputs from organic fertilizer (kg N ha-1, not including manure or digestate) applied to field *n* (specified by the user)

*Norg\_fert\_applied(field n)* Organic N fertilizer applied to field *n* (kg ha-1)

### Crop residue N inputs

**Calculates the N storage in residues for each field and year. The decomposition of the C residue pools is calculated as a fraction of the total pool. That fraction is then used for the N fraction of the C pools and calculated how much N is released from the N pool through the decomposition of the C fraction.**

**Crop nitrogen content is calculated using** **Eq. 2.5.2‑4 - Eq. 2.5.2‑7**

*Calculates the starting AG N pool*

**Eq. 2.6.2‑1**

*Calculates the inputs of N from crop residues (from last year’s crop)*

**Eq. 2.6.2‑2**

Adds the crop residue N to the N pool corresponding to the young C pools, but subtracts the N contained in the young pool fraction that is decomposed

**Eq. 2.6.2‑3**

where

*AGresidueN(crop)* Aboveground residue N (kg N ha-1)

*CptoSoil* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*NP* N concentration in the product (kg kg-1) (**Table 7**)

*NS* N concentration in the straw (kg kg-1) (**Table 7**)

*AGresidueN(t,field n)* Aboveground residue N pool (kg N ha-1) in field *n* in year *t*

*GrainN* N content of the grain returned to the soil (kg N ha-1), calculated in **Eq. 2.5.2‑14**

*StrawN* N content of the straw returned to the soil (kg N ha-1), calculated in **Eq. 2.5.2‑15**

*re* Climate/management factor

*ky* Decomposition rate constant for young pool

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*Calculates the starting BG N pool*

**Eq. 2.6.2‑4**

*Calculates N inputs from crop residues (from last year’s crop)*

**Eq. 2.6.2‑5**

For perennial forages (hay):

**Eq. 2.6.2‑6**

**Eq. 2.6.2‑7**

where

*BGresidueN(crop)* Belowground residue N (kg N ha-1)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

*Nr* N concentration in the roots (kg kg-1) (**Table 7**)

*Ne* N concentration in the extra root (kg kg-1) (**Table 7**)

*BGresidueN(t,fieldn)* Belowground residue N pool (kg N ha-1)

*RootN* N content of the root returned to the soil (kg N ha-1), calculated in **Eq. 2.5.6‑4**

*ExudateN* N content of the exudates returned to the soil (kg N ha-1), calculated in **Eq. 2.5.6‑5**

*re* Climate/management factor

*ky* Decomposition rate constant for young pool

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*Sr* Root turnover fraction

**Calculation of N exported with crop residues**

**Eq. 2.6.2‑8**

where

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*Cag(exported)* C exported as residues from the farm (kg C kg-1)

*Ns* N concentration of straw (kg kg-1)

### Manure N inputs

Total annual N inputs to soil in livestock manure (farm-produced and imported manure, dung and urine directly deposited by grazing livestock) and anaerobic digestate (after all direct and indirect N losses related to land application) are estimated in **Sections 4.7.2, 4.9.5.2 and 5.6.2**.

Calculation of *Nm* at the starting point (t=0)

**Eq. 2.6.3‑1**

Calculation of *Nm* after the starting point (t>0)

**Eq. 2.6.3‑2**

where

*Nm(t,field n)* Manure residue N pool (kg N ha-1) in field *n* in year *t*

*Total\_Nmodel(t,field n)* Total N in manure (farm-produced + imported stored manure + manure from grazing animals) and anaerobic digestate N inputs to soil (after direct and indirect N losses following land application) to field *n* in year *t* (kg N), calculated as the sum of the values estimated using **Eq. 4.7.2‑1** (for farm-produced and imported manure applied to land), **Section 4.9.7.2** (for anaerobic digestate applied to land) and **Eq. 5.6.2‑1** (for dung and urine deposited directly on pasture by grazing animals) - Note: this includes N added to soil from all livestock types grazing on field *n* in year *t*

*area(field n)* Area of field *n* (ha)

*re* Climate/management factor

*ky* Decomposition rate constant for young pool

### Mineralization

**Calculates the mineralization of N from residues in correlation with the decomposition of the respective residue C fraction. Also takes into account N release or immobilisation by the soil C pool. While the N released is added to the mineral N pool, immobilisation will draw from both the mineral and the organic N pool.**

Calculation of *NCropResidues* at the starting point (t=0)

**Eq. 2.6.4‑1**

Calculation of *NCropResidues* after the starting point (t>0)

**Eq. 2.6.4‑2**

Calculation of *Nmin* from the decomposition of old C

**Eq. 2.6.4‑3**

where

*AGresidueN(crop)* Aboveground residue N (kg N ha-1)

*BGresidue N(crop)* Belowground residue N (kg N ha-1)

*Nm(t,field n)* Manure residue N pool (kg N ha-1)

*NCropResiduesN (field n)* Availability of N from residue decomposition (kg N ha-1) on field *n*

*NON (field n)* Available organic N on field *n* (kg N ha-1)

*re* Climate/management factor

*O* Old pool SOC (kg ha-1)

*ky* Decomposition rate constant for young pool

*OldcarbonN* C to N ratio

Holos V4 will use the following constant values:

*OldcarbonN* 1/10 (IPCC 2019, Eq. 11.8)

### Direct emissions from inputs

**Calculates the emission for each field and year independently. The following assumptions apply:**

* N mineralization emissions are calculated specifically for the C change within one field
* Crop residue emissions from residue exports are allotted to the farm of residue origin
* Emissions are calculated based on the specified farm soil texture
* N2O emissions from the decay of residues containing biologically-fixed N are included
* The soil texture, where not specified in **Table 13**, has no effect (RF = 1)
* No till and reduced tillage are combined into conservation tillage
* Irrigation iterates the base EF directly in the year where irrigation takes place, RF adjustments apply regardless
* For all perennials systems, the N source and tillage regime have no effect (RF=1)
* For rotations with partial perennials, the perennial RF will apply including in the year of termination (for pasture that is directly reseeded without interruption the perennial RF is maintained)
* The tillage RF is applied specifically for the tillage of a year
* Different N sources are calculated separately
* Atmospheric deposition, if specified, is treated as synthetic fertilizer

#### Nitrous Oxide

**Eq. 2.6.5‑1**

**Eq. 2.6.5‑2**

**Eq. 2.6.5‑3**

**Eq. 2.6.5‑4**

**Eq. 2.6.5‑5**

**Eq. 2.6.5‑6**

where

*N2O-NSNdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from synthetic fertilizer application to field *n* in year *t*

*EFi,\_\_\_,l,m,n* Emission factor considering the impact of the N source on the cropping system and site dependent factors associated with rainfall, topography, soil texture, N source type, tillage, cropping system and moisture management (kg N2O-N kg-1 N) for ecodistrict ‘‘*i*’’

*N2O-NCRNdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from crop residues and N mineralization on field *n* in year *t*

*N2O-NCRNdirect\_export(t,farm)* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of crop residue emissions exported from the farm in year *t*

*N2O-NCRNmindirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from N mineralization on field *n* in year *t*

*N2O-NONdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from organic fertilizer application to field *n* in year *t*

*N2O-Nmanuredirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.1‑1**), anaerobic digestate (see **Section 4.9.1**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.3.1‑4** – **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-Nmanuredirect\_leftover(t,field n)* Direct N2O emissions (kg N2O-N ha-1) from leftover manure (calculated using **Eq. 4.6.1‑6**) and digestate (see **Section 4.9.1**)applied to field *n* in year *t*

*N2O-NONdirect\_export(t,farm)* Direct N2O emissions (kg N2O-N ha-1) resulting from organic fertilizer exported from the farm in year *t* (as if applied)

*N2O-Nmanuredirect\_export(t,farm)* Direct N2O emissions (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (**Eq. 4.6.1‑9**)

**Note:** The term *NON\_export(t,farm)* is a placeholder for exports of non-manure organic fertilizer from the farm. Currently, in Holos V4, it is not possible for the model user to export non-manure organic fertilizer, but this feature may be incorporated into a future version of Holos.

**Note:** Emissions of direct N2O from the land application of livestock manure (from field-specific and leftover application of farm-produced manure and imported manure) and emissions from exported manure (as if applied) are calculated in **Section 4.6**. Emissions from the land application of digestate (field-specific and leftover applications) are estimated in **Section 4.9.1** and emissions from dung and urine deposited directly on pasture by grazing animals are estimated in **Section 5.3**.

#### Nitric Oxide

**Eq. 2.6.5‑7**

**Eq. 2.6.5‑8**

**Eq. 2.6.5‑9**

**Eq. 2.6.5‑10**

**Eq. 2.6.5‑11**

**Eq. 2.6.5‑12**

where

*NO-NSN(t,field n)* NO emissions (kg NO-N ha-1) resulting from synthetic fertilizer application to field *n* in year *t*

*NO-NCRN(t,field n)* NO emissions (kg NO-N ha-1) resulting from crop residues on field *n* in year *t*

*NO-NCRN\_export(t,farm)* NO emissions (kg NO-N ha-1) resulting from from the sum of crop residue emissions exported from the farm in year *t*

*NO-NCRNmin(t,field n)* NO emissions (kg NO-N ha-1) resulting from N mineralization on field *n* in year *t*

*NO-NON(t,field n)* NO emissions (kg NO-N ha-1) resulting from organic fertilizer application to field *n* in year *t*

*NO-NON\_export(t,farm)* NO emissions (kg NO-N ha-1) resulting from the sum of applications of organic fertilizer exported from the farm (as if applied) in year *t*

Holos V4 will use the following constant values:

*NOratio* 0.1

*NOratio* Ratio of NO to N2O

### Indirect emissions

#### Leaching and runoff fraction

**Eq. 2.6.6‑1**

Rochette et al. 2008

**Eq. 2.6.6‑2**

where

*FracNleach* Fraction of N lost by leaching and runoff (kg N (kg N)-1)

*P* Growing season precipitation (May – October)

*PE* Growing season potential evapotranspiration (May – October)

*P* and *PE* are provided as defaults using the average of 1980-2010 data (Marshall et al. 1999, Newlands et al. 2011).

#### Leaching and runoff from cropland (including annual crops, perennial forages and improved grassland/pasture)

**Calculates the emissions from field and/or crop.**

##### Calculation of indirect N2O emissions based on the amount of N leached

Losses of N2O-N and NO3-N from land-applied manure via leaching are estimated in **section 4.6.4**

**Eq. 2.6.6‑3**

**~~Eq. 2.6.6‑4~~**

**Eq. 2.6.6‑5**

**Eq. 2.6.6‑6**

**Eq. 2.6.6‑7**

where

*N2O-N\_\_\_leach(t,field n)* N emissions due to leaching and runoff (kg N2O-N ha-1) from \_\_\_N source applied to field *n* in year *t*

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFleach* Emission factor for leaching and runoff [kg N2O-N (kg N)-1] – see box below

*N2O-Nmanureleach(t,field n)* N2O-N emissions as a result of N leaching (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.4‑1**), anaerobic digestate (see **Section 4.9.4**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.4‑3** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-Nmanureleach\_leftover(t,field n)* N2O-N emissions as a result of N leaching (kg N2O-N ha-1) from leftover manure (calculated using **Eq. 4.6.4‑2**) and digestate (see **Section 4.9.4**)applied to field *n* in year *t*

*N2O-NONleach\_export(t,farm)* N2O emissions as a result of N leaching (kg N2O-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

Holos V4 will use the following constant values:

*EFleach* 0.011 (IPCC 2019)

*N2O-Nmanureleach\_export(t,farm)* N2O emissions (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.4‑3**)

##### Calculation of the actual amount of N leached

**Eq. 2.6.6‑8**

**~~Eq. 2.6.6‑9~~**

**Eq. 2.6.6‑10**

**Eq. 2.6.6‑11**

**Eq. 2.6.6‑12**

where

*NO3-N\_\_\_leach(t,field n)* N emissions due to leaching and runoff (kg NO3-N ha-1) from \_\_\_N source applied to field *n* in year *t*

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFleach* Emission factor for leaching and runoff [kg N2O-N (kg N)-1]

*NO3-Nmanureleach(t,field* n) NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.4‑6**), anaerobic digestate (see **Section 4.9.4**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.4‑5** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*NO3-Nmanureleach\_leftover(t,field n)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from leftover manure (calculated using **Eq. 4.6.4‑7**) and digestate (see **Section 4.9.4**)applied to field *n* in year *t*

*NO3-NONleach\_export(t,farm)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

*NO3-Nmanureleach\_export(t,farm)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.4‑8**)

**Note:** We removed the accounting of CRN (crop residual nitrogen) from the calculation to avoid double counting. This is because CRN becomes part of the soil carbon pools, the decomposition of which drives the calculation of N mineralization. In this sense, CRN leaching is accounted for by the N mineralization.

#### Emissions due to volatilization

**Calculates the emissions from field and/or crop.**

##### Calculation of indirect N2O emissions based on the amount of N volatilized.

**Eq. 2.6.6‑13**

Bouwman et al. 2002

where

*FracNvolatilizationsoil* Fraction of N lost by volatilization (kg N (kg N)-1)

*Croptype* Annual or perennial (**Table 14**)

*Fertilizertype* Urea, urea ammonium nitrate, anhydrous ammonia or other synthetic N (**Table 14**)

*Applicationmethod* Broadcast or incorporated (**Table 14**) – broadcast application is assumed for perennials

*SoilpH* Below or above pH 7.25 (**Table 14**)

*SoilCEC* Below or above 250 mmol kg-1 (**Table 14**)

*Temperaturecoefficient* Constant -0.402 (**Table 14**)

**Eq. 2.6.6‑14**

**Eq. 2.6.6‑15**

**Eq. 2.6.6‑16**

where

*N2O-N\_\_\_volatilization(t,field n)* N emissions due to volatilization from \_\_\_N source (kg N2O-N) applied to field *n* in year *t* (synthetic N and organic N are considered)

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1]

*N2O-Nallmanurevolatilization(t,field n)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced (incl. leftover manure) and imported manure (**Eq. 4.6.3‑5**), anaerobic digestate (see **Section 4.9.3**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.3‑4** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-NONvolatilization\_export(t,fiarm)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

*N2O-Nmanurevolatilization\_export(t,farm)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.3‑3**)

Holos V4 will use the following constant values:

*EFvolatilization* 0.014 (wet) for Atlantic Canada, QC, ON, and Fraser valley  
0.005 (dry) for MB, SK, AB and interior BC 1 (IPCC 2019)

1 In IPCC (2019), Table 11.3: Disaggregation by climate for *EFvolatilization* (based on long-term averages): Wet climates occur in temperate and boreal zones where the ratio of annual precipitation (P):potential evapotranspiration (PE) >1; Dry climates occur in temperate and boreal zones where the ratio of annual P:PE <1

##### Calculation of the actual amount of N volatilized

**Eq. 2.6.6‑17**

**Eq. 2.6.6‑18**

**Eq. 2.6.6‑19**

where

*NH3\_\_\_(t,field n)* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3\_Nallmanure(t,field n)\_adju* Adjusted NH3-N emissions via volatilization (kg NH3-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced (incl. leftover manure) and imported manure (**Eq. 4.6.3‑11**), anaerobic digestate (see **Section 4.9.3.1**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.3‑6** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*NH3\_NON\_export(t,fiarm)* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1) exported from the farm in year *t*

*NH3\_Nmanure\_export(t,farm)\_adju* Adjusted NH3-N emissions via volatilization (kg NH3-N ha-1) from manure exported from the farm in year *t* (as if applied), calculated using **Eq. 4.6.3‑9**

### Adjust active pools

#### Synthetic N

**Eq. 2.6.7‑1**

**Eq. 2.6.7‑2**

**Eq. 2.6.7‑3**

#### Crop residue N

**Eq. 2.6.7‑4**

**Eq. 2.6.7‑5**

#### Mineralized N

**Eq. 2.6.7‑6**

**Eq. 2.6.7‑7**

#### Organic N

**Eq. 2.6.7‑8**

**Eq. 2.6.7‑9**

**Eq. 2.6.7‑10**

**Eq. 2.6.7‑11**

### Closing the N budget

#### N pool

The SN, CRN, CRNmin, and ON pools empty into the mineralN and microbeN pools and are = 0 thereafter (until they are restarted in the following year if inputs occur).

**Eq. 2.6.8‑1**

**Eq. 2.6.8‑2**

**Eq. 2.6.8‑3**

**Eq. 2.6.8‑4**

where

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

#### N requirements for carbon change and crop growth

**Calculates the ratio of the two N pools**

**If NmineralN > NmicrobeN**

**Eq. 2.6.8‑5**

**If NmicrobeN > NmineralN**

**Eq. 2.6.8‑6**

where

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

**Calculates the N demand from C moving from the Young pools into the Old pool.**

**Eq. 2.6.8‑7**

**If NmineralN > NmicrobeN**

**Eq. 2.6.8‑8**

**Eq. 2.6.8‑9**

**If NmicrobeN > NmineralN**

**Eq. 2.6.8‑10**

**Eq. 2.6.8‑11**

where

*ΔONdemand* N requirement for the C transitioning from the young to the old pool

*Yag* Young pool soil organic C – aboveground (kg C ha-1)

*Ybg* Young pool soil organic C – belowground (kg C ha-1)

Ym Young pool SOC – manure (kg C ha-1)

*re* Climate/management factor

*ky* Decomposition rate constant for young pool

*kO* Decomposition rate constant for old pool

*hag* Young pool humification constant – aboveground

*hbg* Young pool humification constant – belowground

hm Young pool humification constant – manure

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

**Calculates the N uptake of the new crop (current year) – all biomass fractions are therefore set to 100%.**

**Eq. 2.6.8‑12**

**If NmineralN > NmicrobeN**

**Eq. 2.6.8‑13**

**Eq. 2.6.8‑14**

**If NmicrobeN > NmineralN**

**Eq. 2.6.8‑15**

**Eq. 2.6.8‑16**

where

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

*Nfixation* Amount of N supplied to the crop through biological N fixation (kg N ha-1), the model default is 70% of the crop demand is fixated (H. Janzen)

*Cp* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

*moisturecontent (crop n)* Moisture content of crop yield (w/w) (**Table 7**, by crop)

*NP* N concentration in the product (kg N kg-1) (**Table 7**)

*NS* N concentration in the straw (kg N kg-1) (**Table 7**)

*Nr* N concentration in the roots (kg N kg-1) (**Table 7**)

*Ne* N concentration in the extra root (kg N kg-1) (**Table 7**)

*Nm* Amount of N (kg N ha-1) applied

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

#### Balance the pools

#### **If NmicrobeN(t,field n)>0**

#### **Eq. 2.6.8‑17**

#### **If NmicrobeN(t,field n)<=0**

#### **Eq. 2.6.8‑18**

#### **Eq. 2.6.8‑19**

#### **Eq. 2.6.8‑20**

#### **If NmineralN(t,field n)>0**

#### **Eq. 2.6.8‑21**

After Scheer et al. 2020

**If NmineralN(t,field n)<=0**

**Eq. 2.6.8‑22**

**Eq. 2.6.8‑23**

**In the first year (t=0)**

**Eq. 2.6.8‑24**

**Eq. 2.6.8‑25**

**In the following year (t>0)**

**Eq. 2.6.8‑26**

**Eq. 2.6.8‑27**

**If NmineralN(t,field n)<0**

**Eq. 2.6.8‑28**

**Eq. 2.6.8‑29**

where

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmicrobedeathN* Release of N from the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

*N2-Nloss* Denitrification of mineral N as N2 (kg N2-N ha-1) on field *n*

*NmicrobeNbalance* Interannual N balance in the microbial overflow pool (kg N ha-1) on field *n*

*NmineralNbalance* Interannual N balance in the mineral overflow pool (kg N ha-1) on field *n*

Holos V4 will use the following constant values:

*Microbedeath* 0.20 (expert opinion M. Gorzelak)

### Total emissions

#### Nitrogen losses from a field

##### Nitrous Oxide

**Calculate the emissions for each field, crop, and year (i.e., on a (*t, field n*) basis):**

**Eq. 2.6.9‑1**

**Eq. 2.6.9‑2**

**Eq. 2.6.9‑3**

**Eq. 2.6.9‑4**

where

*N2O-NSN* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from fertilizer application

*N2O-NCRN* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from crop residues and N mineralization

*N2O-NCRNmin* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from N mineralization

*N2O-NON* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from the application of organic fertilizers (incl. manure and digestate); *N2O-NONdirect* is calculated based on **Eq. 2.6.5‑5**; *N2O-NONleach* is calculated based on **Eq. 2.6.6‑6**; *N2O-NONvolatilization* is calculated based on **Eq. 2.6.6‑15**

*N2O-Ndirect* Direct N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-Nindirect* Indirect N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-Ntotal* N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N ha-1)

*N2O-N\_\_\_\_\_(area, field n, crop n)* N2O emissions by source/summary from field *n* and crop *n* (kg N2O-N field *n*-1)

*areafield n* area (ha) of field *n*

##### Nitric Oxide

**Eq. 2.6.9‑5**

**Eq. 2.6.9‑6**

where

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N ha-1)

*NO-Ntotal* Sum of NO emissions due to N inputs (kg NO-N ha-1)

*NO-N\_\_\_(area, field n, crop n)*  NO emissions by source/summary from field *n* and crop *n* (kg NO-N field *n*-1)

##### Nitrate leaching

**Eq. 2.6.9‑7**

**Eq. 2.6.9‑8**

where

*NO3-N\_\_\_leach* Leached N from \_\_\_N source (kg NO3-N ha-1)

*NO3-N \_total \_leach* Sum of leached N from \_\_\_N source (kg NO3-N ha-1)

*NO3-N \_\_\_leach (area, field n, crop n)* Leached N by source/summary from field *n* and crop *n* (kg NO3-N field *n*-1)

##### Ammonia Volatilization

**Eq. 2.6.9‑9**

**Eq. 2.6.9‑10**

where

*NH3-N\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3-N total* Sum of volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3-N \_\_\_ (area, fieldn, crop n)*  Volatilized NH3-N by source/summary from field *n* and crop *n* (kg NH3-N field *n*-1)

##### Denitrification

**Eq. 2.6.9‑11**

where

*N2-Nloss* Denitrification of mineral N as N2 (kg N2-N ha-1)

*N2-Nloss (area, field n, crop n)* N2 from field *n* and crop *n* (kg N2-N fieldn-1)

#### N emissions from a crop

**This is a recalculation of the N2O emissions summarised by crop.**

**Eq. 2.6.9‑12**

**Eq. 2.6.9‑13**

**Eq. 2.6.9‑14**

**Eq. 2.6.9‑15**

**Eq. 2.6.9‑16**

where

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N crop-1)

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N crop-1)

*NO3-N \_\_\_leach* Leached N from \_\_\_N source (kg NO3-N crop-1)

*NH3-N\_\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N crop-1)

*N2-Nloss* N2 loss (kg N2-N crop-1)

#### N emissions from a year

**This is a recalculation of the N2O emissions summarised by year.**

**Eq. 2.6.9‑17**

**Eq. 2.6.9‑18**

**Eq. 2.6.9‑19**

**Eq. 2.6.9‑20**

**Eq. 2.6.9‑21**

where

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N yr-1)

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N yr-1)

*NO3-N \_\_\_leach* Leached N from \_\_\_N source (kg NO3-N yr-1)

*NH3-N\_\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N yr-1)

*N2-Nloss* N2 loss (kg N2-N yr-1)

#### Sum of emissions related to export of biomass

**Eq. 2.6.9‑22**

**Eq. 2.6.9‑23**

**Eq. 2.6.9‑24**

**Eq. 2.6.9‑25**

**Eq. 2.6.9‑26**

where

*N2O-Ntotaldirect\_export* Sum of direct N2O emissions due to export of biomass from the farm (kg N2O-N yr-1)

*N2O-NCRN\_directexport* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of crop residue emissions that have been exported from the farm

*N2O-NON\_directexport* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of applications of manure exported from the farm

*NO-Ntotal\_export* Sum of NO emissions due to export of biomass from the farm (kg NO-N yr-1)

*NO-NCRN\_export* NO emissions (kg NO-N ha-1) resulting from the sum of crop residue emissions that have been exported from the farm

*NO-NON\_export* NO emissions (kg NO-N ha-1) resulting from the sum of applications of manure exported from the farm

*N2O-Ntotalindirect\_export* Sum of indirect N2O emissions due to export of biomass from the farm (kg N2O-N yr-1)

*N2O-NONleach\_export* N2O emissions (kg N2O -N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.6.6‑7**

*N2O-NONvolatilization\_export* N2O emissions (kg N2O -N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.6.6‑16**

*NO3-Ntotal\_export* Sum of NO3 emissions due to export of biomass from the farm (kg NO3-N yr-1)

*NO3-NONleach\_export* NO3 emissions (kg NO3-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.6.6‑12**

*NH3-Ntotal\_export* Sum of NH3 emissions due to export of biomass from the farm (kg NH3-N yr-1)

*NH3-NON\_export* NH3 emissions (kg NH3-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.6.6‑19**

#### Conversion factors

**Eq. 2.6.9‑27**

**Eq. 2.6.9‑28**

**Eq. 2.6.9‑29**

**Eq. 2.6.9‑30**

**Eq. 2.6.9‑31**

where

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N yr-1)

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N yr-1)

*NO3-N \_\_\_leach* Leached N from \_\_\_N source (kg NO3-N yr-1)

*NH3-N\_\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N yr-1)

*N2-Nloss* N2 loss (kg N2-N yr-1)

*N2O\_\_\_\_\_* N2O emission source/summary (kg N2O yr-1)

*NO\_\_\_\_\_* NO emissions source/summary (kg NO yr-1)

*NO3 \_\_\_leach* Leached N from \_\_\_N source (kg NO3 yr-1)

*NH3\_\_\_\_* Volatilized NH3 from \_\_N source (kg NH3 yr-1)

*N2loss* N2 loss (kg N2 yr-1)

44/28 Conversion from N2O-N to N2O

30/14 Conversion from NO-N to NO

62/14 Conversion from NO3-N to NO3

17/14 Conversion from NH3-N to NH3

14/28 Conversion from N2-N to N2

#### Monthly Emission Estimate

On the Farm Information Form, there is a Soil N2O breakdown section. This section contains a box for each month whereby the user will enter the percentage of yearly soil N2O emissions allocated to that month. The sum of monthly emissions should equal 100%.

These are calculated for each crop (including annual crops, perennial forages, fallow and improved grassland/pasture), and for mineralized N. **Please note:** this does not apply to land-applied manure or digestate.

##### N2O

**Eq. 2.6.9‑32**

where

*N2O \_\_\_\_\_* Direct N2O emissions resulting N source (kg N2O month-1)

*N2O \_\_\_\_\_* Direct N2O emissions resulting from the presence of mineral N (kg N2O year-1)

*Monthly%* Percentage of annual emissions allocated to month (defaults in **Table 15**)

#### Budgeting of Nitrogen

##### Input

These values are used for this equation before any of the emissions or other losses are calculated

**Eq. 2.6.9‑33**

##### Emissions

**Eq. 2.6.9‑34**

##### Nitrogen Uptake

**Eq. 2.6.9‑35**

##### Total Output

**Eq. 2.6.9‑36**

##### Overflow pools and N2 losses

**These values are taken from the end of the N cycle (section 2.6.7) after all calculations have been completed.**

**Eq. 2.6.9‑37**

## Multi-year estimation of nitrous oxide (adapted Liang et al. 2020 with N carryover) for IPCC Tier 2 Carbon model

(by R. Kröbel, A. McPherson and S.J. Pogue)

### Synthetic and organic N fertilizer applications (not manure)

For N synthetic fertilizer applications inputs for each field are calculated independently**. Results are provided by field and/or crop.**

Fertilizer input calculations should be completed for all fertilized crop types, including annual crops, perennial forages and improved grassland/pasture (improved grassland/pasture is pasture that is fertilized and/or irrigated).

**Eq. 2.7.1‑1**

**Eq. 2.7.1‑2**

where

*NSN(field n)* N inputs from synthetic fertilizer (kg N ha-1) on field *n* (provided through **Eq. 2.6.1‑2**, if not specified otherwise by the user)

*N\_fert\_applied(field n)* N fertilizer applied on field *n* (kg ha-1)

*N\_fert\_deposit(field n)* N deposition on field *n* (kg ha-1) (user defined)

Holos V4 will use the following constant values:

*N\_fert\_deposit(field n)* 5 kg N ha-1 (Janzen et al., 2003)

Organic fertilizer applications (user-defined only until default options are added to the model) are treated as different from synthetic fertilizers:

**Eq. 2.7.1‑3**

where

*NON(field n)* N inputs from organic fertilizer (kg N ha-1, not including manure or digestate) on field *n* (specified by the user)

*Norg\_fert\_applied(field n)* Organic N fertilizer applied on field *n* (kg ha-1)

### Crop residue N inputs

**Calculates the N storage in residues for each field and year. The decomposition of the C residue pools determines the rate of N release from the N pool representations of Active, Slow, and Passive pools.**

#### For annual crops included in the National Inventory Report (NIR) methodology

**Eq. 2.7.2‑1**

where

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*AGDM(t,field n)* Aboveground biomass (kg ha-1), from **Eq. 2.2.2‑2**

*NS* N concentration in the straw (kg kg-1) (**Table 7**)

**Eq. 2.7.2‑2**

where

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

*BGR(T)* Belowground biomass (kg) from **Eq. 2.2.2‑4**

*Nr* N concentration in the roots (kg kg-1) (**Table 7**)

#### For crops not in the NIR

*Calculates the inputs of N from crop residues (from last year’s crop)*

**For annual crops, perennials and rangeland:**

**Eq. 2.7.2‑3**

**Eq. 2.7.2‑4**

where

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

*CptoSoil* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*NP* N concentration in the product (kg kg-1) (**Table 7**)

*NS* N concentration in the straw (kg kg-1) (**Table 7**)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

*Nr* N concentration in the roots (kg kg-1) (**Table 7**)

*Ne* N concentration in the extra root (kg kg-1) (**Table 7**)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

**For root crops:**

**Eq. 2.7.2‑5**

**Eq. 2.7.2‑6**

where

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

*CptoSoil* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*NP* N concentration in the product (kg kg-1) (**Table 7**)

*NS* N concentration in the straw (kg kg-1) (**Table 7**)

*Ce* C input from extra-root material (kg ha-1)

*Ne* N concentration in the extra root (kg kg-1) (**Table 7**)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

**For silage crops and cover crops:**

**Eq. 2.7.2‑7**

**Eq. 2.7.2‑8**

where

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

*CptoSoil* C input from product (kg ha-1)

*NP* N concentration in the product (kg kg-1) (**Table 7**)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

*Nr* N concentration in the roots (kg kg-1) (**Table 7**)

*Ne* N concentration in the extra root (kg kg-1) (**Table 7**)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

**For fallow:**

**Eq. 2.7.2‑9**

**Eq. 2.7.2‑10**

where

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

**For manure:**

**Eq. 2.7.2‑11**

where

*Manure-N(t,field n)* Manure N input (kg N ha-1)

*Total\_Nmodel(t,field n)* Total N in manure (farm-produced + imported stored manure + manure from grazing animals) and anaerobic digestate N inputs to soil (after direct and indirect N losses following land application) to field *n* in year *t* (kg N), calculated as the sum of the values estimated using **Eq. 4.7.2‑1** (for farm-produced and imported manure applied to land), **Section 4.9.7.2** (for anaerobic digestate applied to land) and **Eq. 5.6.2‑1** (for dung and urine deposited directly on pasture by grazing animals) - Note: this includes N added to soil from all livestock types grazing on field *n* in year *t*

*area(field n)* Area of field *n* (ha)

**Eq. 2.7.2‑12**

where

*Manure-Nexport(t,farm)* N in manure exported from the farm (kg N ha-1)

*Total\_Nmanure\_export(t)* Total N (kg N) exported from the farm in manure in year *t*, calculated using**Eq. 4.6.1‑8**

#### Total input

**Eq. 2.7.2‑13**

where

*CropR-N(t,field n)* Total organic N input (t N ha-1)

*AG-N(t,field n)* Aboveground residue N (kg N ha-1)

*BG-N(t,field n)* Belowground residue N (kg N ha-1)

*Manure-N(t,field n)* Manure N input (kg N ha-1) to field *n* in year *t*

**Eq. 2.7.2‑14**

where

*NCropResidue\_export(t,field n)* N in crop residues exported from the field (kg N ha-1)

*AGDMexported(T)* Aboveground residue DM for crop T (kg DM ha-1) that is exported from the field

*NS* N concentration in the straw (kg kg-1) (**Table 7**)

**Eq. 2.7.2‑15**

where

*NCropResidue\_export(t,farm)* N in crop residues exported from the farm (kg N ha-1)

### Mineralization

**Calculates the mineralization of N from residues in correlation with the decomposition of the respective residue C fraction. Also takes into account N release or immobilisation by the soil C pool. While the N released is added to the mineral N pool, immobilisation will draw from both the mineral and the organic N pool.**

**Eq. 2.7.3‑1**

IPCC 2019, Eq. 5.0G

where:

*βN* N input to the metabolic dead organic matter C component (t N ha-1 year-1)

*CropR-N(t,field n)* Total organic N input (t N ha-1)

LC Lignin content of C input (proportion) (**Table 9** for default values, otherwise compile country-specific values)

NC N fraction of the C input (proportion) (**Table 9** for default values, otherwise compile country-specific values)

**Eq. 2.7.3‑2**

IPCC 2019, Eq. 5.0G

where:

*αN* N input to the active soil C sub-pool (t N ha-1)

*f1* Fraction of metabolic dead organic matter decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f2* Fraction of structural dead organic matter decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f3* Fraction of structural dead organic matter decay products transferred to the slow sub-pool (proportion) (**Table 8**)

*f6* Fraction of slow sub-pool decay products transferred to the passive sub-pool (proportion) (**Table 8**)

*f7* Fraction of slow sub-pool decay products transferred to the active sub-pool (proportion) (**Table 8**)

*f8* Fraction of passive sub-pool decay products transferred to the active sub-pool (proportion) (**Table 8**)

**Eq. 2.7.3‑3**

IPCC 2019, Eq. 5.0B

where:

*ActiveNy\** Steady state active sub-pool SOC-N stock given conditions in year y (t N ha-1)

*ka* Decay rate for active SOC sub-pool (year-1) (**value cannot be higher than 1**)

*αN* N input to the active soil C sub-pool (t N ha-1)

**Eq. 2.7.3‑4**

IPCC 2019, Eq. 5.0B

where:

*Activey* Active sub-pool SOC-N stock in year y (t N ha-1)

*Activey-1* Active sub-pool SOC-N stock in previous year (t N ha-1)

**Eq. 2.7.3‑5**

IPCC 2019, Eq. 5.0C

where:

*SlowNy* Slow sub-pool SOC-N stock in y (t N ha-1)

*CropR-N(t,field n)* Total organic N input (t N ha-1)

*LC* Lignin content of C input (proportion) (see **Table 9**) for default values, otherwise compile country-specific values)

*f3* Fraction of structural component decay products transferred to the slow sub-pool (proportion) (see **Table 8**)

*ActiveNy\** Steady state active sub-pool SOC-N stock given conditions in year y (t N ha-1)

*ka* Decay rate for active C sub-pool in the soil (year-1)

*f4* Fraction of active sub-pool decay products transferred to the slow sub-pool (proportion) (see **Eq. 2.2.2‑16**)

*ks* Decay rate for slow SOC sub-pool (year-1) (**value cannot be higher than 1**)

**Eq. 2.7.3‑6**

IPCC 2019, Eq. 5.0C

where:

*SlowNy-1* Slow sub-pool SOC-N stock in previous year (t N ha-1)

*SlowNy\** Steady state slow sub-pool SOC-N stock given conditions in year y (t N ha-1)

**Eq. 2.7.3‑7**

IPCC 2019, Eq. 5.0D

where:

*PassiveNy* Passive sub-pool SOC-N stock in year y (t N ha-1)

*kp* Decay rate for passive SOC sub-pool (year-1) (**value cannot be higher than 1**)

*ActiveNy\** Steady state active sub-pool SOC-N stock given conditions in year y (t N ha-1)

*ka* Decay rate for active C sub-pool in the soil (year-1)

*SlowNy\** Steady state slow sub-pool SOC-N stock given conditions in year y (t N ha-1)

*ks* Decay rate for slow SOC sub-pool (year-1)

*f5* Fraction of active sub-pool decay products transferred to the slow sub-pool (proportion) (see **Table 8**)

*f6* Fraction of slow sub-pool decay products transferred to the passive sub-pool (proportion) (see **Table 8**)

**Eq. 2.7.3‑8**

IPCC 2019, Eq. 5.0D

where:

*PassiveNy-1* Passive sub-pool SOC-N stock in previous year (t N ha-1)

*Passivey\** Steady state passive sub-pool SOC-N given conditions in year y (t N ha-1)

**Eq. 2.7.3‑9**

**Eq. 2.7.3‑10**

where:

*ActiveNy\** Steady state active sub-pool SOC-N stock given conditions in year y (t N ha-1)

*Activey-1* Active sub-pool SOC-N stock in previous year (t N ha-1)

*SlowNy-1* Slow sub-pool SOC-N stock in previous year (t N ha-1)

*SlowNy\** Steady state slow sub-pool SOC-N stock given conditions in year y (t N ha-1)

*PassiveNy-1* Passive sub-pool SOC-N stock in previous year (t N ha-1)

*Passivey\** Steady state passive sub-pool SOC-N given conditions in year y (t N ha-1)

#### Calculate C Input to the active sub-pool for each year of the inventory period

##### Calculate the C input to the metabolic dead organic matter component (β)

The N input to the metabolic dead organic matter N component (βN) is calculated using  **Eq. 2.7.3‑1**.

##### Calculate the C input to the active soil carbon sub-pool (α)

The C input to the active soil C sub-pool (α) is calculated using **Eq. 2.7.3‑2**.

**Repeat steps 2.7.3.1.1 and 2.7.3.1.2 for all other years in the inventory period to derive annual values for α and β**

#### Calculate the Water Effect on Decomposition

##### Monthly water effect on decomposition (*wi*)

The parameters *mappeti* (ratio of total precipitation to total potential evapotranspiration for month *i* and *wi* (monthly water effect on decomposition) are estimated using **Eq. 2.2.2‑13** and **Eq. 2.2.2‑14**.

For each month in a year, calculate the ratio of total precipitation to total potential evapotranspiration. If the ratio is ≤1.25 then set the value of *mappeti* for the month to the estimated ratio; if the ratio is >1.25 then set the value of *mappeti* for the month to 1.25; set *wi* for months with irrigation to 0.775.

##### Calculate water effect on decomposition for each month (wi) in a year

For land area under irrigation management, set the water effect on decomposition for the month (*wi* ) to 0.775.

##### Annual water effect on decomposition (*w fac*)

The annual water effect on decomposition is calculated using **Eq. 2.2.2‑15**.

Repeat steps **2.2.5.1** and **2.2.5.3** to to calculate the water effect (*w fac*) on decomposition for all years in the inventory period.

#### Calculate the Temperature Effect on Decomposition

##### Monthly temperature effect on decomposition (*Ti*)

For each month in the year, calculate the temperature effect on decomposition (*T i*) is calculated using **Eq. 2.2.2‑11** and the values for maximum monthly temperature for decomposition (*t max*), optimum temperature for decomposition (*t opt*) and the monthly average temperature (*temp i*).

**Note: If the monthly average air temperature is ≤45 °C, use the calculated value of *Ti*;**

**If the monthly average temperature is >45 °C, set *Ti* equal to 0.**

##### Annual temperature effect on decomposition (*Tfac*)

The annual temperature effect on decomposition is calculated using **Eq. 2.2.2‑12**.

**Repeat steps 2.2.2.5.1 to 2.2.6.2 to calculate the annual temperature effect on decomposition for all years in the inventory.**

#### Calculate the size of the passive N Sub-pool

##### Decay rate for the passive SOC-N sub-pool in the soil *(k p*).

To calculate the decay rate for the passive SOC soil sub-pool, use **Eq. 2.2.2‑21**.

##### Steady state stock for the passive sub-pool SOC-N stock (*PassiveN y*\*)

To calculate PassiveNy\*, use **Eq. 2.7.3‑7**

##### Passive sub-pool SOC-N stock (*PassiveNy*)

PassiveNy is calculated by determining the additional increase or decrease in SOC-N from the previous year in the inventory. This is estimated using **Eq. 2.7.3‑8**.

**Note: If the estimated *kp* value is above 1, then set the value of *kp* to 1 in the equation for calculating *Passivey*.**

**Repeat steps 2.7.3.4.1 to 2.7.3.4.3 to calculate the passive SOC-N stocks for all years in the inventory.**

#### Calculate the size of the slow SOC-N Sub-pool

##### Decay rate for the slow SOC-N sub-pool in the soil (*ks*)

*Ks* is estimated using **Eq. 2.2.2‑20**.

##### Steady state stock for the slow SOC-N sub-pool (*SlowNy*\*)

*SlowNy\** is estimated using **Eq. 2.7.3‑5**.

##### Slow sub-pool SOC-N (*SlowNy*)

The slow sub-pool SOC-N stock (*SlowNy*) is estimated by determining the additional increase or decrease in SOC-N from the previous year in the inventory using **Eq. 2.7.3‑6**.

**Note: if the estimated *ks* value is above 1, then set the value of *ks* to 1 in the equation for calculating *Slowy*.**

**Repeat steps 2.7.3.5.1 and 2.7.3.5.3 to calculate the slow SOC sub-pool stocks for all years in the inventory.**

#### Calculate the size of the active SOC-N sub-pool

##### Decay rate for the active SOC-N sub-pool in the soil (*ka*)

To estimate *Ka* use **Eq. 2.2.2‑19**.

##### Steady state stock for the active SOC-N sub-pool (*ActiveNy*\*)

To calculate *ActiveNy\**, use **Eq. 2.7.3‑3**.

##### Active sub-pool SOC-N stock (*ActiveN y*)

The active SOC-N stock (*ActiveNy*) is estimated by determining the additional increase or decrease in SOC-N from the previous year in the inventory using **Eq. 2.7.3‑4**.

**Note: if the estimated *ka* value is above 1, then set the value of *ka* to 1 in the equation for calculating *Active y*.**

**Repeat steps 2.7.3.6.1 and 2.7.3.6.3 to calculate the active SOC sub-pool stocks for all years in the inventory.**

#### Calculate the total annual SOC stock change

##### SOC stock (*SOCy*) for each grid cell or region

**If the user supplied a custom soil C content, the run-up period will be run using average default year (10yr average ahead of the start year) and used to calculate the fractions of the pools from the pools after 5 yrs (default that can be adjusted):**

**Eq. 2.7.3‑11**

**Eq. 2.7.3‑12**

**Eq. 2.7.3‑13**

where:

*SOCuser-supplied* SOC-N stock as supplied by the user (t C ha-1)

*ActiveNyi* Active sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1)

*SlowNyi* Slow sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1)

*PassiveNyi* Passive sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1)

*FractionActive* Pool fraction as determined by the run with default input for the location (dimensionless)

*FractionSlow* Pool fraction as determined by the run with default input for the location (dimensionless)

*FractionPassive* Pool fraction as determined by the run with default input for the location (dimensionless)

*OldcarbonN* C to N ratio

*SlowcarbonN* C to N ratio (user specified)

*ActivecarbonN* C to N ratio (user specified)

Holos V4 will use the following constant values:

*OldcarbonN* 1/10 (EQ 11.8; IPCC 2019)

*SlowcarbonN* 1/20 (preliminary default)

*ActivecarbonN* 1/40 (preliminary default)

Use the following equation to estimate *SOC-Nyi* for each grid cell or region by summing the SOC in the active (*ActiveNy*), slow (*SlowNy*) and passive (*PassiveNy*) sub-pools:

**Eq. 2.7.3‑14**

IPCC 2019, Eq. 5.0A

where:

*SOC-Nyi* SOC-N stock at the end of the current year y for grid cell or region (t N ha-1)

*Activeyi* Active sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1) (**Eq. 2.7.3‑4**)

*Slowyi* Slow sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1) (**Eq. 2.7.3‑6**)

*Passiveyi* Passive sub-pool SOC-N stock in year *y* for grid cell or region (t N ha-1) (**Eq. 2.7.3‑8**)

##### Stock change factor (𝐹𝑆𝑂𝐶𝑖) for each grid cell or region

**Eq. 2.7.3‑15**

IPCC 2019, Eq. 5.0A

where:

*F-NSOCi* Annual stock change factor for mineral soils in grid cell or region *i* (t N ha-1)

*SOC-Nyi* SOC-N stock at the end of the current year y for grid cell or region (t N ha-1)

*SOC-N(y-1)i* SOC-N stock at the end of the previous year for grid cell or region (t N ha-1)

##### Total change in SOC stock (*ΔCMineral*)

The total change in the SOC stock us calculated by multiplying the stock change factor (𝐹𝑆𝑂𝐶𝑖) by the area of the grid cell or region *i* (*A*), and summing the changes across all land included in the Tier 2 steady-state method.

**Eq. 2.7.3‑16**

IPCC 2019, Eq. 5.0A

where:

*ΔNSOC* Annual SOC-N stock change factor for mineral soil, summed across all *i* grid cells or regions (t N)

*F-NSOCi* Annual stock change factor for mineral soils in grid cell or region *i* (t N ha-1)

*Ai* Area of grid cell or region (ha)

### Direct emissions from inputs

**Calculates the emission for each field and year independently. The following assumptions apply:**

* Manure emissions are calculated only for the field where the manure was applied.
* N mineralization emissions are calculated specifically for the C change within one field.
* Crop residue emissions from residue exports are allotted to the farm of residue origin.
* Manure emissions from manure exports are allotted to the farm of residue origin.
* Emissions are calculated based on the specified farm soil texture.
* N2O emissions from the decay of residues containing biologically-fixed N are included.
* The soil texture, where not specified in **Table 13**, has no effect (RF = 1).
* No till and reduced tillage are combined into conservation tillage.
* Irrigation iterates the base EF directly in the year where irrigation takes place, RF adjustments apply regardless.
* For all perennials systems, the N source and tillage regime have no effect (RF=1).
* For rotations with partial perennials, the perennial RF will apply including in the year of termination (for pasture that is directly reseeded without interruption the perennial RF is maintained).
* The tillage RF is applied specifically for the tillage of a year.
* Different N sources are calculated separately.
* Atmospheric deposition, if specified, is treated as synthetic fertilizer.

#### Nitrous Oxide

**Eq. 2.7.4‑1**

**Eq. 2.7.4‑2**

**Eq. 2.7.4‑3**

**Eq. 2.7.4‑4**

**Eq. 2.7.4‑5**

**Eq. 2.7.4‑6**

where

*N2O-NSNdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from synthetic fertilizer application to field *n* in year *t*

*EFi,\_\_\_,l,m,n* Emission factor considering the impact of the N source on the cropping system and site dependent factors associated with rainfall, topography, soil texture, N source type, tillage, cropping system and moisture management (kg N2O-N kg-1 N) for ecodistrict ‘‘*i*’’

*N2O-NCRNdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from crop residues and N mineralization on field *n* in year *t*

*N2O-NCRNdirect\_export(t,farm)* N2O emissions (kg N2O-N ha-1) resulting from from the sum of crop residue emissions that have been exported from the farm in year *t*

*N2O-NCRNmindirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from N mineralization on field *n* in year *t*

*N2O-NONdirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from organic fertilizer application to field *n* in year *t*

*N2O-Nmanuredirect(t,field n)* Direct N2O emissions (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.1‑1**), anaerobic digestate (see **Section 4.9.1**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.3.1‑4** – **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-Nmanuredirect\_leftover(t,field n)* Direct N2O emissions (kg N2O-N ha-1) from leftover manure (calculated using **Eq. 4.6.1‑6**) and digestate (see **Section 4.9.1**)applied to field *n* in year *t*

*N2O-NONdirect\_export(t,farm)* Direct N2O emissions (kg N2O-N ha-1) resulting from organic fertilizer exported from the farm in year *t* (as if applied)

*N2O-Nmanuredirect\_export(t,farm)* Direct N2O emissions (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (**Eq. 4.6.1‑9**)

**Note:** The term *NON\_export(t,farm)* is a placeholder for exports of non-manure organic fertilizer from the farm. Currently, in Holos V4, it is not possible for the model user to export non-manure organic fertilizer, but this feature may be incorporated into a future version of Holos.

**Note:** Emissions of direct N2O from the land application of livestock manure (from field-specific and leftover application of farm-produced manure and imported manure) and emissions from exported manure (as if applied) are calculated in **Section 4.6**. Emissions from the land application of digestate (field-specific and leftover applications) are estimated in **Section 4.9.1** and emissions from dung and urine deposited directly on pasture by grazing animals are estimated in **Section 5.3**.

#### Nitric Oxide

**Eq. 2.7.4‑7**

**Eq. 2.7.4‑8**

**Eq. 2.7.4‑9**

**Eq. 2.7.4‑10**

**Eq. 2.7.4‑11**

**Eq. 2.7.4‑12**

where

*NO-NSN(t,field n)* NO emissions (kg NO-N ha-1) resulting from synthetic fertilizer application to field *n* in year *t*

*NO-NCRN(t,field n)* NO emissions (kg NO-N ha-1) resulting from crop residues on field *n* in year *t*

*NO-NCRN\_export(t,farm)* NO emissions (kg NO-N ha-1) resulting from from the sum of crop residue emissions exported from the farm in year *t*

*NO-NCRNmin(t,field n)* NO emissions (kg NO-N ha-1) resulting from N mineralization on field *n* in year *t*

*NO-NON(t,field n)* NO emissions (kg NO-N ha-1) resulting from organic fertilizer application to field *n* in year *t*

*NO-NON\_export(t,farm)* NO emissions (kg NO-N ha-1) resulting from the sum of applications of organic fertilizer exported from the farm (as if applied) in year *t*

*NOratio* Ratio of NO to N2O

Holos V4 will use the following constant values:

*NOratio* 0.1

### Indirect emissions

#### Leaching and runoff fraction

**Eq. 2.7.5‑1**

Rochette et al. 2008

**Eq. 2.7.5‑2**

where

*FracNleach* Fraction of N lost by leaching and runoff (kg N (kg N)-1)

*P* Growing season precipitation (May – October)

*PE* Growing season potential evapotranspiration (May – October)

*P* and *PE* are provided as defaults using the average of 1980-2010 data (Marshall et al. 1999, Newlands et al. 2011).

#### Leaching and runoff from cropland (including annual crops, perennial forages and improved grassland/pasture)

**Calculates the emissions from field and/or crop.**

##### Calculation of indirect N2O emissions based on the amount of N leached.

Losses of N2O-N and NO3-N from land-applied manure via leaching are estimated in **section 4.6.4**

**Eq. 2.7.5‑3**

**~~Eq. 2.7.5‑4~~**

**Eq. 2.7.5‑5**

**Eq. 2.7.5‑6**

**Eq. 2.7.5‑7**

where

*N2O-N\_\_\_leach(t,field n)* N emissions due to leaching and runoff (kg N2O-N ha-1) from \_\_\_N source applied to field *n* in year *t*

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFleach* Emission factor for leaching and runoff [kg N2O-N (kg N)-1] – see box below

*N2O-Nmanureleach(t,field n)* N2O-N emissions as a result of N leaching (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.4‑1**), anaerobic digestate (see **Section 4.9.4**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.4‑3** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-Nmanureleach\_leftover(t,field n)* N2O-N emissions as a result of N leaching (kg N2O-N ha-1) from leftover manure (calculated using **Eq. 4.6.4‑2**) and digestate (see **Section 4.9.4**)applied to field *n* in year *t*

*N2O-NONleach\_export(t,farm)* N2O emissions as a result of N leaching (kg N2O-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

*N2O-Nmanureleach\_export(t,farm)* N2O emissions (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.4‑3**)

Holos V4 will use the following constant values:

*EFleach* 0.011 (IPCC 2019)

##### Calculation of the actual amount of N leached.

**Eq. 2.7.5‑8**

**~~Eq. 2.7.5‑9~~**

**Eq. 2.7.5‑10**

**Eq. 2.7.5‑11**

**Eq. 2.7.5‑12**

where

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1)

*NO3-N\_\_\_leach(t,field n)* N emissions due to leaching and runoff (kg NO3-N ha-1) from \_\_\_N source applied to field *n* in year *t*

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFleach* Emission factor for leaching and runoff [kg N2O-N (kg N)-1]

*NO3-Nmanureleach(t,field* n) NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced and imported manure (**Eq. 4.6.4‑6**), anaerobic digestate (see **Section 4.9.4**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.4‑5** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*NO3-Nmanureleach\_leftover(t,field n)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from leftover manure (calculated using **Eq. 4.6.4‑7**) and digestate (see **Section 4.9.4**)applied to field *n* in year *t*

*NO3-NONleach\_export(t,farm)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

*NO3-Nmanureleach\_export(t,farm)* NO3-N emissions as a result of N leaching (kg NO3-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.4‑8**)

**Note:** We removed the accounting of CRN (crop residual nitrogen) from the calculation to avoide double counting. This is because CRN becomes part of the soil carbon pools, the decomposition of which drives the calculation of N mineralization. In this sense, CRN leaching is accounted for when in fact mineralized.

#### Emissions due to volatilization

**Calculates the emissions from field and/or crop.**

##### Calculation of indirect N2O emissions based on the amount of N volatilized.

**Eq. 2.7.5‑13**

Bouwman et al. 2002

where

*FracNvolatilizationsoil* Fraction of N lost by volatilization (kg N (kg N)-1)

*Croptype* Annual or perennial (**Table 14**)

*Fertilizertype* Urea, urea ammonium nitrate, anhydrous ammonia or other synthetic N (**Table 14**)

*Applicationmethod* Broadcast or incorporated (**Table 14**) – broadcast application is assumed for perennials

*SoilpH* Below or above pH 7.25 (**Table 14**)

*SoilCEC* Below or above 250 mmol kg-1 (**Table 14**)

*Temperaturecoefficient* Constant -0.402 (**Table 14**)

**Eq. 2.7.5‑14**

**Eq. 2.7.5‑15**

where

**Eq. 2.7.5‑16**

where

*N2O-N\_\_\_volatilization* N emissions due to volatilization from \_\_\_N source (kg N2O-N) applied to field *n* in year *t* (synthetic N and organic N are considered)

*N\_\_\_\_* Availability of \_\_\_\_\_N (kg N ha-1) to field *n* in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1]

*N2O-Nallmanurevolatilization(t,field n)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced (incl. leftover manure) and imported manure (**Eq. 4.6.3‑5**), anaerobic digestate (see **Section 4.9.3**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.3‑4** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*N2O-NONvolatilization\_export(t,farm)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from organic fertilizer exported from the farm in year *t* (as if applied)

*N2O-Nmanurevolatilization\_export(t,farm)* N2O-N emissions as a result of N volatilization (kg N2O-N ha-1) from manure exported from the farm in year *t* (as if applied) (calculated using **Eq. 4.6.3‑3**

Holos V4 will use the following constant values:

*EFvolatilization* 0.014 (wet) for Atlantic Canada, QC, ON, and Fraser valley  
0.005 (dry) for MB, SK, AB and interior BC 1 (IPCC 2019)

1 In IPCC (2019), Table 11.3: Disaggregation by climate for *EFvolatilization* (based on long-term averages): Wet climates occur in temperate and boreal zones where the ratio of annual precipitation (P):potential evapotranspiration (PE) >1; Dry climates occur in temperate and boreal zones where the ratio of annual P:PE <1

##### Calculation of the actual amount of N volatilized.

**Eq. 2.7.5‑17**

**Eq. 2.7.5‑18**

**Eq. 2.7.5‑19**

where

*NH3\_\_\_(t,field n)* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3\_Nallmanure(t,field n)\_adju* Adjusted NH3-N emissions via volatilization (kg NH3-N ha-1) from manure applied to specific fields; this is the sum of emissions from the application of farm-produced Iincl. Leftover manure) and imported manure (**Eq. 4.6.3‑11**), anaerobic digestate (see **Section 4.9.3.1**) and manure deposited directly on pasture by grazing animals (derived from **Eq. 5.4.3‑5** - **Note:** if more than one livestock type is grazed on field *n* in year *t*, this value is the sum of manure N from these multiple livestock groups)

*NH3\_NON\_export(t,farm)* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1) exported from the farm in year *t*

*NH3\_Nmanure\_export(t,farm)\_adju* Adjusted NH3-N emissions via volatilization (kg NH3-N ha-1) from manure exported from the farm in year *t* (as if applied), calculated using **Eq. 4.6.3‑9**

### Adjust active pools

#### Synthetic N

**Eq. 2.7.6‑1**

**Eq. 2.7.6‑2**

**Eq. 2.7.6‑3**

#### Crop residue N

**Eq. 2.7.6‑4**

**Eq. 2.7.6‑5**

#### Mineralized N

**Eq. 2.7.6‑6**

**Eq. 2.7.6‑7**

#### Organic N

**Eq. 2.7.6‑8**

**Eq. 2.7.6‑9**

**Eq. 2.7.6‑10**

### Closing the N budget

#### N pool

The SN, CRN, CRNmin, and ON pools empty into the mineralN and microbeN pools and are = 0 thereafter (until they are restarted in the following year if inputs occur).

**Eq. 2.7.7‑1**

**Eq. 2.7.7‑2**

**Eq. 2.7.7‑3**

**Eq. 2.7.7‑4**

where

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

#### N requirements for Carbon Change and Crop growth

**Calculates the ratio of the two N pools**

**If NmineralN > NmicrobeN**

**Eq. 2.7.7‑5**

**If NmicrobeN > NmineralN**

**Eq. 2.7.7‑6**

where

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

**Calculates the N demand from C pools.**

**If NmineralN > NmicrobeN**

**Eq. 2.7.7‑7**

**Eq. 2.7.7‑8**

**If NmicrobeN > NmineralN**

**Eq. 2.7.7‑9**

**Eq. 2.7.7‑10**

where

*SOC-Nrequirement(t, field n)* Combined N requirement for the IPCC Tier 2 C pools (active, slow, and passive)

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

**Calculates the N uptake of the new crop (current year) – all biomass fractions are therefore set to 100%.**

**Eq. 2.7.7‑11**

**If NmineralN > NmicrobeN**

**Eq. 2.7.7‑12**

**Eq. 2.7.7‑13**

**If NmicrobeN > NmineralN**

**Eq. 2.7.7‑14**

**Eq. 2.7.7‑15**

where

*NPoolratio* Ratio between mineral and microbial N

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

*Nfixation* Amount of N supplied to the crop through biological N fixation (kg N ha-1), the model default is 70% of the crop demand is fixated (H. Janzen)

*Cp* C input from product (kg ha-1)

*Cs* C input from straw (kg ha-1)

*Cr* C input from roots (kg ha-1)

*Ce* C input from extra-root material (kg ha-1)

*moisturecontent (crop n)* Moisture content of crop yield (w/w) (**Table 7**, by crop)

*NP* N concentration in the product (kg N kg-1) (**Table 7**)

*NS* N concentration in the straw (kg N kg-1) (**Table 7**)

*Nr* N concentration in the roots (kg N kg-1) (**Table 7**)

*Ne* N concentration in the extra root (kg N kg-1) (**Table 7**)

*Nm* Amount of N (kg N ha-1) applied

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

#### Balance the pools

**If NmicrobeN(t,field n)>0**

**Eq. 2.7.7‑16**

**If NmicrobeN(t,field n)<=0**

**Eq. 2.7.7‑17**

**Eq. 2.7.7‑18**

**Eq. 2.7.7‑19**

**If NmineralN(t,field n)>0**

**Eq. 2.7.7‑20**

After Scheer et al. 2020

**If NmineralN(t,field n)<=0**

**Eq. 2.7.7‑21**

**Eq. 2.7.7‑22**

**In the first year (t=0)**

**Eq. 2.7.7‑23**

**Eq. 2.7.7‑24**

**In the following year (t>0)**

**Eq. 2.7.7‑25**

**Eq. 2.7.7‑26**

**If NmineralN(t,field n)<0**

**Eq. 2.7.7‑27**

**Eq. 2.7.7‑28**

where

*NmicrobeN* Availability of N in the microbial pool (kg N ha-1) on field *n*

*NmicrobedeathN* Release of N from the microbial pool (kg N ha-1) on field *n*

*NmineralN* Availability of mineral N (kg N ha-1) on field *n*

*N2-Nloss* Denitrification of mineral N as N2 (kg N2-N ha-1) on field *n*

*NmicrobeNbalance* Interannual N balance in the microbial overflow pool (kg N ha-1) on field *n*

*NmineralNbalance* Interannual N balance in the mineral overflow pool (kg N ha-1) on field *n*

Holos V4 will use the following constant values:

*Microbedeath* 0.20 (expert opinion M. Gorzelak)

### Total emissions

#### Nitrogen losses from a field

##### Nitrous Oxide

**Calculate the emission for each field, crop, and year (i.e., on a (*t, field n*) basis):**

**Eq. 2.7.8‑1**

**Eq. 2.7.8‑2**

**Eq. 2.7.8‑3**

**Eq. 2.7.8‑4**

where

*N2O-NSN* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from fertilizer application

*N2O-NCRN* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from crop residues and N mineralization

*N2O-NCRNmin* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from N mineralization

*N2O-NON* N2O emissions (kg N2O-N kg-1 N ha-1) resulting from the application of organic fertilizers (incl. manure and digestate); *N2O-NONdirect* is calculated based on **Eq. 2.7.4‑5**; *N2O-NONleach* is calculated based on **Eq. 2.7.5‑6**; *N2O-NONvolatilization* is calculated based on **Eq. 2.7.5‑15**

*N2O-Ndirect* Direct N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-Nindirect* Indirect N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-Ntotal* N2O emissions due to crop N inputs (kg N2O-N ha-1)

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N ha-1)

*N2O-N\_\_\_\_\_(area, field n, crop n)* N2O emissions by source/summary from field *n* and crop *n* (kg N2O-N field *n*-1)

*areafield n* area(ha) of field n

##### Nitric Oxide

**Eq. 2.7.8‑5**

**Eq. 2.7.8‑6**

where

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N ha-1)

*NO-Ntotal* Sum of NO emissions due to N inputs (kg NO-N ha-1)

*NO-N\_\_\_\_(area, field n, crop n)*  NO emissions by source/summary from field *n* and crop *n* (kg NO-N field *n*-1)

##### Nitrate leaching

**Eq. 2.7.8‑7**

**Eq. 2.7.8‑8**

where

*NO3-N\_\_\_leach* Leached N from \_\_\_N source (kg NO3-N ha-1)

*NO3-N \_total \_leach* Sum of leached N from \_\_\_N source (kg NO3-N ha-1)

*NO3-N \_\_\_leach (area, field n, crop n)* Leached N by source/summary from field *n* and crop *n* (kg NO3-N field*n*-1)

##### Ammonia Volatilization

**Eq. 2.7.8‑9**

**Eq. 2.7.8‑10**

where

*NH3-N\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3-N total* Sum of volatilized NH3-N from \_\_N source (kg NH3-N ha-1)

*NH3-N \_\_\_ (area, fieldn, crop n)*  Volatilized NH3-N by source/summary from field *n* and crop *n* (kg NH3-N field*n*-1)

##### Denitrification

**Eq. 2.7.8‑11**

where

*N2-Nloss* Denitrification of mineral N as N2 (kg N2-N ha-1)

*N2-Nloss (area, field n, crop n)* N2 from field *n* and crop *n* (kg N2-N field *n*-1)

#### N emissions from a crop

**This is a recalculation of the N2O emissions summarised by crop.**

**Eq. 2.7.8‑12**

**Eq. 2.7.8‑13**

**Eq. 2.7.8‑14**

**Eq. 2.7.8‑15**

**Eq. 2.7.8‑16**

where

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N crop-1)

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N crop-1)

*NO3-N \_\_\_leach* Leached N from \_\_\_N source (kg NO3-N crop-1)

*NH3-N\_\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N crop-1)

*N2-Nloss* N2 loss (kg N2-N crop-1)

#### N emissions from a year

**This is a recalculation of the N2O emissions summarised by year.**

**Eq. 2.7.8‑17**

**Eq. 2.7.8‑18**

**Eq. 2.7.8‑19**

**Eq. 2.7.8‑20**

**Eq. 2.7.8‑21**

where

*N2O-N\_\_\_\_\_* N2O emission source/summary (kg N2O-N yr-1)

*NO-N\_\_\_\_\_* NO emissions source/summary (kg NO-N yr-1)

*NO3-N \_\_\_leach* Leached N from \_\_\_N source (kg NO3-N yr-1)

*NH3-N\_\_\_\_* Volatilized NH3-N from \_\_N source (kg NH3-N yr-1)

*N2-Nloss* N2 loss (kg N2-N yr-1)

#### Sum of emissions related to export of biomass

**Eq. 2.7.8‑22**

**Eq. 2.7.8‑23**

**Eq. 2.7.8‑24**

**Eq. 2.7.8‑25**

**Eq. 2.7.8‑26**

where

*N2O-Ntotaldirect\_export* Sum of direct N2O emissions due to export of biomass from the farm (kg N2O-N yr-1)

*N2O-NCRN\_directexport* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of crop residue emissions that have been exported from the farm

*N2O-NON\_directexport* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of applications of manure exported from the farm

*NO-Ntotal\_export* Sum of NO emissions due to export of biomass from the farm (kg NO-N yr-1)

*NO-NCRN\_export* NO emissions (kg NO-N ha-1) resulting from the sum of crop residue emissions that have been exported from the farm

*NO-NON\_export* NO emissions (kg NO-N ha-1) resulting from the sum of applications of manure exported from the farm

*N2O-Ntotalindirect\_export* Sum of indirect N2O emissions due to export of biomass from the farm (kg N2O-N yr-1)

*N2O-NONleach\_export* N2O emissions (kg N2O-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.7.5‑7**

*N2O-NONvolatilization\_export* N2O emissions (kg N2O-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.7.5‑16**

*NO3-Ntotal\_export* Sum of NO3 emissions due to export of biomass from the farm (kg NO3-N yr-1)

*NO3-NONleach\_export* NO3 emissions (kg NO3-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.7.5‑12**

*NH3-Ntotal\_export* Sum of NH3 emissions due to export of biomass from the farm (kg NH3-N yr-1)

*NH3-NON\_export* NH3 emissions (kg NH3-N ha-1) resulting from the sum of applications of organic N exported from the farm, derived from **Eq. 2.7.5‑19**

#### Conversion factors

See Section 2.6.9.5.

#### Monthly Emission Estimate

On the Farm Information Form, there is a soil N2O breakdown section. This section contains a box for each month whereby the user will enter the percentage of yearly soil N2O emissions allocated to that month. The sum of monthly emissions should equal 100%.

These are calculated for each crop (including annual crops, perennial forages, fallow and improved grassland/pasture), and for mineralized N. **Please note:** this does not apply to land-applied manure or digestate.

##### N2O

**Eq. 2.7.8‑27**

where

*N2O \_\_\_\_\_* Direct N2O emissions resulting N source (kg N2O month-1)

*N2O \_\_\_\_\_* Direct N2O emissions resulting from the presence of mineral N (kg N2O year-1)

*Monthly%* Percentage of annual emissions allocated to month (defaults in **Table 15**)

#### Budgeting of Nitrogen

##### Input

These values are used for this equation before any of the emissions or other losses are calculated

**Eq. 2.7.8‑28**

##### Emissions

**Eq. 2.7.8‑29**

##### Nitrogen Uptake

**Eq. 2.7.8‑30**

##### Total Output

**Eq. 2.7.8‑31**

##### Overflow pools and N2 losses

**These values are taken from the end of the N cycle (section 2.7.7) after all calculations have been completed.**

**Eq. 2.7.8‑32**

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# Livestock enteric methane emissions

(by A.W. Alemu and S.J. Pogue)

## Beef cattle

**Management data are input for each management period. Emissions are calculated on a daily basis.**

**Assumptions:**

* Cattle feed intake is equal to energy requirements
* All feed is utilized - waste feed emissions are not accounted for
* All cows are pregnant and 5 kg of protein is retained for every pregnancy
* Calves consume 1% of their own body weight as solid food
* Calves retain 20% of protein intake from dry feed and 40% of protein intake from milk
* Enteric CH4 emissions from calves are calculated using the IPCC Ym approach only (section 3.1.2)

### Enteric CH4 emissions from beef cattle (except calves)

#### IPCC Ym approach for beef cattle (except calves)

**Enteric CH4 calculations should be completed for each cattle group (except calves).**

**Eq. 3.1.1‑1**

where

*Weight* Weight (kg head-1)

*ADG* Average daily gain (kg head-1 day-1), calculated using **Eq. 3.1.1‑7**

*days* Total number of days since start of management period

*initial\_wt* Initial weight (kg head-1) (**Table 16**, by beef cattle group, or user-defined)

##### Net energy requirements

***Cfadusted* represents the influence of temperature on the maintenance coefficient, *Cf*, and varies by day due to daily average temperature.**

**Eq. 3.1.1‑2**

IPCC 2019, Eq. 10.2

where

*Cfadjusted* Maintenance coefficient adjusted for temperature (MJ day-1 kg-1)

*Cf* Baseline maintenance coefficient (MJ day-1 kg-1) (**Table 16**, by beef cattle group)

*Temperature* Average daily temperature **(upper limit = 20 °C, if temperature > 20 °C or if cattle are housed in a barn, use 20 °C)**

**While this is calculated and labelled as *Cf* in the model code, it is labelled *“Maintenance coefficient”*  in the model interface.**

By default, daily *Temperature* data are obtained fromfrom the NASA POWER data access viewer (<https://power.larc.nasa.gov/data-access-viewer/>) - the model user can override these data using custom daily climate data. In the event that neither NASA daily climate data nor user-defined daily climate data are available, Holos uses 1991-2020 climate normals for each SLC polygon as a default.

**Eq. 3.1.1‑3**

IPCC 2019, Eq. 10.3

where

*NEmaintenance* Net energy for maintenance (MJ head-1 day-1)

**Eq. 3.1.1‑4**

IPCC 2019, Eq. 10.4

where

*NEactivity* Net energy for activity (MJ head-1 day-1)

*Ca* Feeding activity coefficient (**Table 17**, by activity type)

**For lactating beef cows only (use only when cows are lactating – when # calves>0):**

**Eq. 3.1.1‑5**

IPCC 2019, Eq. 10.8

where

*NElactation* Net energy for lactation (MJ head -1 day-1)

*milk\_production* Milk production (kg head-1 day-1 )

*fat\_content* Fat content (%)

*#calves* Number of calves

*#cows* Number of cows

Holos V4 will use the following constant values:

*milk\_production* 8 (kg head-1 day-1)

*fat\_content* 4 (%)

**#calves/#cows adjusts for cows without calves and averages energy for lactation over all individuals.**

**For pregnant beef cows only:**

**Eq. 3.1.1‑6**

IPCC 2019, Eq. 10.13

where

*NEpregnancy* Net energy for pregnancy (MJ head-1 day-1)

*0.1* Pregnancy coefficient – IPCC (2019) default for cattle and buffalo of 0.1 is used

This equation averages pregnancy energy requirements over the entire year.

##### Average daily gain, net energy for gain

**For all beef cattle groups, default ADG gain values are provided for each management period, based on default start and end weights and the number of days in each management period – as for most of the other inputs in Holos, this information can be overridden with user-defined inputs****.**

**Eq. 3.1.1‑7**

where

*ADG* Average daily gain (kg head-1 day-1)

*final\_wt* Final weight (kg head-1) (**Table 16**, by beef cattle group)

*initial\_wt* Initial weight (kg head-1) (**Table 16**, by beef cattle group)

*#days* Number of days – **includes all months where animals >0 are entered**

**For all beef animals (excluding calves):**

**Eq. 3.1.1‑8**

IPCC 2019, Eq. 10.6

where

*NEgain* Net energy for gain (MJ head-1 day-1)

*Weight* Weight (kg head-1)

*final\_wt* Final weight of animal (kg) (**Table 16**)

*Cd* Gain coefficient (**Table 16**), by cattle group)

*ADG* Average daily gain (kg head-1 day-1)

##### Ratios of net energy available to digestible energy

**Eq. 3.1.1‑9**

IPCC 2019, Eq. 10.14

where

*REM* Ratio of net energy available in diet for maintenance to digestible energy consumed

*TDN* Percent total digestible nutrients in feed (**Table 18**, by diet)

***TDN* value is to be entered as a percentage (e.g. as 81 not 0.81).**

**Eq. 3.1.1‑10**

IPCC 2019, Eq. 10.15

where

*REG* Ratio of net energy available in diet for gain to digestible energy consumed

##### Gross energy intake

**Eq. 3.1.1‑11**

IPCC 2019, Eq. 10.16

where

*GEI* Gross energy intake (MJ head-1 day-1)

##### Enteric CH4 emission

**Eq. 3.1.1‑12**

Derived from IPCC 2019, Eq. 10.21

where

*CH4enteric\_rate* Enteric CH4 emission rate (kg head-1 day-1)

*Ym* Methane conversion factor (**Table 18**, by diet)

55.65 Energy content of CH4 (MJ kg-1 CH4)

*AR* Additive reduction factor (**Table 19**, by additive)

**Eq. 3.1.1‑13**

where

*CH4enteric* Enteric CH4 emissions by animal group (kg CH4 day-1)

*#cattle* Number of beef cattle

#### Other enteric CH4 estimates

In addition to using the default IPCC (2019) Ym conversion factors to estimate enteric CH4 emissions from beef cattle, the inclusion of different mathematical equations (linear and exponential) with varying input requirements provides the model user (and in particular researchers) with additional options. For beef cattle, the selected equations were developed and evaluated by Lingen et al. (2019). Four equations are selected and divided into two groups based on the concentration of forage in the diet. Two equations are for diets containing ≥ 25% forage DM (high forage diets, **Eq. 3.1.1‑14** and **Eq. 3.1.1‑15**) and the remaining two equations are for diets containing < 25% forage DM (low forage diets, **Eq. 3.1.1‑16** and **Eq. 3.1.1‑17).**

##### High forage diets ***(≥ 25% dietary forage)***

If the percentage of forage in the diet ≥ 25% (of DM), equations B1 and B2 are used to estimate enteric CH4 emissions

**Eq. 3.1.1‑14**

Escobar-Bahamondes et al. 2017, Eq. AL-OR

where

*CH4enteric(B1)-rate* Enteric CH4 emissions (kg head-1 day-1)

*BW* Body weight (kg)

*Forage* % forage in the diet (% of DM)

*EEI* Ether extract/crude fat intake (kg head-1 day-1)

*GEI* Gross energy intake (MJ head-1 day-1)

Holos V4 uses the following calculation:

***EEI*** =DMI (kg/day) \* [EE concentration in the feed and/or diet (%DM)/100)] + DMI (kg day-1) \* (% Fat supplement added as diet additives/100)

**Eq. 3.1.1‑15**

Van Lingen et al. 2019, Eq. 17

where

*CH4enteric(B2)-rate* Enteric CH4 emission rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

*Forage* Dietary forage (% of DM)

*BW* Body weight (kg)

##### Low forage diets ***(< 25% dietary forage)***

If the percentage of forage in the diet < 25% (of DM), equations B3 and B4 are used to estimate enteric CH4 emissions.

**Eq. 3.1.1‑16**

Escobar-Bahamondes et al. 2017, Eq. LF-MC

where

*CH4enteric(B3)-rate* Enteric CH4 emission rate (kg head-1 day-1)

*BW* Body weight (kg)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

*EEI* Ether extract/crude fat intake (kg head-1 day-1)

*CPI* Crude protein intake (kg head-1 day-1)

*NDFI* Neutral detergent fiber intake (kg head-1 day-1)

*StarchI* Starch intake (kg head-1 day-1)

Holos V4 will use the following calculation:

***CPI*** =DMI (kg/day) \* [CP concentration in the feed or diet (%DM)/100)]

***NDFI*** = DMI (kg/day) \* [NDF concentration in the feed or diet (%DM)/100)]

***Starch*** = DMI (kg/day) \* [Starch concentration in the feed or diet (%DM)/100)]

**Eq. 3.1.1‑17**

Ellis et al. 2009, Eq. N

where

*CH4enteric(B4)-rate* Enteric CH4 emissions rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

*Starch* Dietary starch (% of DM)

*NDF* Dietary neutral detergent fiber (% of DM)

**Eq. 3.1.1‑18**

where

*CH4enteric(n)* Enteric CH4 emissions by animal group (kg CH4 day-1), n = B1, B2, B3, B4

*#cattle* Number of cattle

### Enteric CH4 emissions from beef calves

Enteric CH4 emissions from beef calves are estimated based on a simplified Tier 2 approach from IPCC (2019) for the estimation of daily DMI. Enteric CH4 emissions for this animal group are estimated only for those days when the calves are on a non-milk (i.e., forage) diet. **To calculate enteric CH4 from these calves only when they are feeding (at least partially) on forage, as a default we have assumed that, in addition to consuming milk, calves also graze on forage from 01 July to 31 October (123 days, according to Legesse et al. (2016, 2018) and that they are placed on the same pasture (native or tame) as the cows.** For the remainder of the calf period, the calves are assumed to consume milk only and thus zero enteric CH4 emissions are assumed for these days.

**Eq. 3.1.2‑1**

where

*Weight* Weight (kg head-1)

*ADG* Average daily gain (kg head-1 day-1). Calculated according to **Eq. 3.1.1‑7**

*days* Total number of days since start of management period

*initial\_wt* Initial weight (kg head-1) (**Table 16**, by beef cattle group)

**Eq. 3.1.2‑2**

Derived from IPCC 2019, Eq. 10.17

where

*DMI* DM intake (kg head-1 day-1)

*Weight* Weight (kg head-1)

*NEmf* Estimated dietary net energy concentrationof diet or default values (MJ kg-1) (**Table 20**)

**Note:** for beef and dairy calves on a milk-only diet, the DMI is estimated as: ***DMI = Weight \* 0.01***

**Eq. 3.1.2‑3**

IPCC 2019

where

*GEI* Gross energy intake (MJ head-1 day-1)

18.45 Conversion factor for gross energy per kg of DM (MJ kg-1)

**Use equations (Eq. 3.1.1‑12) and (Eq. 3.1.1‑13) to calculate enteric CH4 emissions for beef calves.**

### Total enteric CH4 emissions

Enteric CH4 emissions should be summed for all relevant management periods and beef cattle groups.

**Eq. 3.1.3‑1**

IPCC 2019, Eq. 10.20

where

*Total\_CH4enteric* Total enteric CH4 emissions from beef cattle (kg CH4 year-1)

*CH4enteric* Enteric CH4 emissions (kg CH4)

## Dairy cattle

**Management data are input for each management period. Emissions are calculated on a daily basis.**

**Assumptions:**

* All cows are pregnant
* All mature dairy cows are lactating
* 5 kg of protein is retained for every pregnancy
* All feed is utilized - waste feed emissions are not accounted for.
* Cattle feed intake is equal to energy requirements
* Milk production is constant throughout year and there is one milk production cycle per year
* Veal calves are milk-fed only (after this, emissions may be calculated in the feedlot scenarios)
* Manure must be applied at least once per year

### Enteric CH4 emissions from dairy cattle (except calves)

#### IPCC Ym approach for dairy cattle (except calves)

**Enteric CH4 calculations should be completed for each dairy cattle group (except calves).**

**Eq. 3.2.1‑1**

where

*Weight* Weight (kg head-1)

*ADG* Average daily gain (kg head-1 day-1), calculated using **Eq. 3.2.1‑6**

*days* Total number of days since start of management period

*initial\_wt* Initial weight (kg head-1) (**Table 16**, by cattle group)

##### Net energy requirements

**Eq. 3.2.1‑2**

IPCC 2019, Eq. 10.3

where

*NEmaintenance* Net energy for maintenance (MJ head-1 day-1)

*Cf* Maintenance coefficient (MJ day-1 kg-1) (**Table 16**, by dairy cattle group)

**Eq. 3.2.1‑3**

IPCC 2019, Eq. 10.4

where

*NEactivity* Net energy for activity (MJ head-1 day-1)

*Ca* Feeding activity coefficient (**Table 17**, by activity type)

**For lactating dairy cows only (use only when cows are lactating – as a default, Holos assumes 305 days lactation per year):**

**Eq. 3.2.1‑4**

IPCC 2019, Eq. 10.8

where

*NElactation* Net energy for lactation (MJ head -1 day-1)

*milk\_production* Milk production (kg head-1 day-1 ), by province (**Table 21**)

*fat\_content* Fat content (%). A default value of 3.71% is used (Canadian Dairy Information Centre)

**Note:** *fat\_content* is entered as a percentage (e.g. as 4 not 0.04)

**For pregnant dairy cows only:**

**Eq. 3.2.1‑5**

IPCC 2019, Eq. 10.13

where

*NEpregnancy* Net energy for pregnancy (MJ head-1 day-1)

*0.1* Pregnancy coefficient – IPCC (2019) default for cattle and buffalo of 0.1 is used

This equation averages pregnancy energy requirements over the entire year.

##### Average daily gain, net energy for gain

**For all dairy cattle:**

**Eq. 3.2.1‑6**

where

*ADG* Average daily gain (kg head-1 day-1)

*initial\_wt* Initial weight (kg head-1) (**Table 16**, by dairy cattle group)

*final\_wt* Final weight (kg head-1) (**Table 16**, by dairy cattle group)

*#days* Number of days – **includes all months where >0 animals are entered**

**Eq. 3.2.1‑7**

IPCC 2019, Eq. 10.6

where

*NEgain* Net energy for gain (MJ head-1 day-1)

*Weight* Weight (kg head-1)

*final\_wtmilkcow* Final weight of animal (kg)

*Cd* Gain coefficient (**Table 16**, by cattle group)

##### Ratios of net energy available to digestible energy

**Eq. 3.2.1‑8**

IPCC 2019, Eq. 10.14

where

*REM* Ratio of net energy available in diet for maintenance to digestible energy consumed

*TDN* Percent total digestible nutrients in feed (**Table 18**, by diet)

***TDN* value is to be entered as a percentage (e.g. as 81 not 0.81).**

**Eq. 3.2.1‑9**

IPCC 2019, Eq. 10.15

where

*REG* Ratio of net energy available in diet for gain to digestible energy consumed

##### Gross energy intake

**Eq. 3.2.1‑10**

IPCC 2019, Eq. 10.16

where

*GEI* Gross energy intake (MJ head-1 day-1)

##### Enteric CH4 emissions

**Eq. 3.2.1‑11**

Derived from IPCC 2019, Eq. 10.21

where

*CH4enteric\_rate* Enteric CH4 emission rate (kg head-1 day-1)

*Ym* CH4 conversion factor (**Table 18**, by diet)

55.65 Energy content of CH4 (MJ kg-1 CH4)

*AR* Additive reduction factor (**Table 19**, by additive)

**Eq. 3.2.1‑12**

where

*CH4enteric* Enteric CH4 emissions by animal group (kg CH4 day-1)

*#cattle* Number of dairy cattle

#### Other enteric CH4 estimates

In addition to using the default IPCC (IPCC 2019) *Ym* conversion factors to estimate enteric CH4 emissions from dairy cattle, the inclusion of different mathematical equations (linear and exponential) with varying input requirements provides the model user (and in particular researchers) with additional options. For dairy cattle, the selected equations were developed and evaluated by Niu et al. (2018) and Benaouda et al. (2019). Four equations were selected and divided into two groups based on the concentration of forage in the diet. Two equations are for diets containing ≥ 25% forage DM (high forage diets, **Eq. 3.2.1‑13** and **Eq. 3.2.1‑14**) and the remaining two equations are for diets containing < 25% forage DM (low forage diets, **Eq. 3.2.1‑15** and **Eq. 3.2.1‑16**).

**Eq. 3.2.1‑13**

Ramin and Huhtanen 2013

where

*CH4enteric(D1)-rate* Enteric CH4 emissions rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

**Eq. 3.2.1‑14**

Mills et al. 2003, Eq. NL1

where

*CH4enteric(D)-rate* Enteric CH4 emissions rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

**Eq. 3.2.1‑15**

Ellis et al. 2007, Eq. 8d

where

*CH4enteric(D3)-rate* Enteric CH4 emissions rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

*ADFI* Acid detergent fiber intake (kg head-1 day-1)

*NDFI* Neutral detergent fiber intake (kg head-1 day-1)

Holos V4 will use the following formulas:

Acid detergent fiber intake (**ADFI**) =DMI (kg d-1) \* [ADF in the diet or feed (% DM)/100)]

Neutral detergent fiber intake (**NDFI**) =DMI (kg d-1) \* [NDF in the diet or feed (% DM)/100)]

**Eq. 3.2.1‑16**

Niu et al. 2018, Eq. 5

where

*CH4enteric(D4)-rate* Enteric CH4 emissions rate (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated using **Eq. 11.3.1‑1**

*EE* Dietary fat/ether extract (% of DM)

*NDF* Dietary neutral detergent fiber (% of DM)

**Eq. 3.2.1‑17**

where

*CH4enteric(n)* Enteric CH4 emissions (kg CH4), n = D1, D2, D3, D4

*#cattle* Number of cattle

### Enteric CH4 emissions from dairy calves

For dairy calves, the following equation is used to calculate enteric CH4 emissions from milk-fed dairy calves.

**Eq. 3.2.2‑1**

IPCC 2019

where

*CH4enteric* Enteric CH4 emissions from dairy calves (kg CH4 day-1)

IPCC (2019) states that “A CH4 conversion factor of zero is assumed for all juveniles consuming only milk (i.e., milk-fed lambs as well as calves)”. Therefore, there are no enteric CH4 emissions associated with milk-fed dairy calves.

### Total enteric CH4 emissions

Emissions should be summed for all relevant management periods and dairy cattle groups.

**Eq. 3.2.3‑1**

IPCC 2019, Eq. 10.20

where

*Total\_CH4enteric* Total enteric CH4 emissions from dairy cattle (kg CH4 year-1)

*CH4enteric* Enteric CH4 emissions (kg CH4), by dairy cattle group

## Sheep

**Management data are input for each management period. Emissions are calculated on a daily basis.**

**Assumptions:**

* The user specifies the number of ewes and number of lambs, from which the number of lambs per ewe (lamb:ewe ratio) is calculated
* The pregnancy twinning rate is based on the current lamb:ewe ratio (assumed static)
* There are no emissions from nursing lambs
* Sheep feed intake is equal to energy requirements
* The sex ratio of the feedlot is 1:1
* All feed is utilized - waste feed emissions are not accounted for
* All barn manure is handled as solid storage (stockpiled) manure and land-applied at least once per year

### Enteric CH4 emissions from sheep

Enteric CH4 calculations should be completed for each sheep group.

**Eq. 3.3.1‑1**

where

*Weight* Weight (kg head-1)

*ADG* Average daily gain (kg head-1 day-1), calculated using **Eq. 3.3.1‑9**

*days* Total number of days since start of management period

*initial\_wt* Initial weight (kg head-1) (**Table 22**, by sheep group)

#### Lamb:ewe ratio

This is calculated only for those months when there are lambs with ewes; the average yearly lamb:ewe ratio is used.

**Eq. 3.3.1‑2**

where

*Lamb\_Ratio* Lamb:ewe ratio

*#lambs* Number of lambs

*#ewes* Number of ewes

#### Net energy requirements

**Eq. 3.3.1‑3**

IPCC 2019, Eq. 10.3

where

*NEmaintenance* Net energy for maintenance (MJ head-1 day-1)

*Cf* Maintenance coefficient (MJ day-1 kg-1) (**Table 22**, by sheep group)

**Eq. 3.3.1‑4**

IPCC 2019, Eq. 10.5

where

*NEactivity* Net energy for activity (MJ head-1 day-1)

*Ca* Feeding activity coefficient (MJ kg-1) (**Table 23**, by activity type)

**For lactating ewes only (use only when ewes are lactating and milk production is unknown – when # lambs>0):**

**Eq. 3.3.1‑5**

Derived from IPCC 2019, Eq. 10.10

where

*NElactation* Net energy for lactation (MJ head -1 day-1)

*WGlamb* Daily pre-weaning weight gain of lamb(s) (**Table 24**, by Lamb:ewe ratio)

5 When milk production is not known, AFRC (1990) indicates that for a single birth, the milk yield is about 5 times the weight gain of the lamb. For multiple births, the total annual milk production can be estimated as five times the increase in combined weight gain of all lambs birthed by a single ewe.

*EVmilk* Energy required to produce 1 kg of milk (MJ kg-1). The default IPCC (2019) *EVmilk* value of 4.6 MJ kg-1 can be used for sheep (AFRC 1993; AFRC 1995), which corresponds to a milk fat content of 7% by weight.

Holos V4 will use the following constant values:

*EVmilk* 4.6 MJ kg-1 (IPCC 2019)

**For lactating ewes only (use only when ewes are lactating and milk production is known – when # lambs>0):**

**Eq. 3.3.1‑6**

IPCC 2019, Eq. 10.9

where

*Milk* Amount of milk produced (kg head-1 day-1). A default value of 2 kg head-1 day-1 is used (based on a value of approximately 2 L per sheep per day (Farm and Food Care Ontario 2016)), assuming that 1 L of milk weighs approx. 1 kg.

**For pregnant ewes only:**

**Eq. 3.3.1‑7**

IPCC 2019, Eq. 10.13

where

*NEpregnancy* Net energy for pregnancy (MJ head-1 day-1)

*Cpreg* Pregnancy coefficient (**Table 25**, by Lamb:ewe ratio)

This equation averages pregnancy energy requirements over the entire year.

**For ewes and rams only:**

**Eq. 3.3.1‑8**

IPCC 2019, Eq. 10.12

where

*NEwool* Net energy for wool production (MJ head-1 day-1)

*EVwool* Energy value of 1 kg of wool (MJ kg-1)

*wool\_production* Wool production (kg year-1) (**Table 22**, by sheep group)

365 Number of days in year

Holos V4 will use the following constant values:

*EVwool* 24 MJ kg-1 (IPCC 2019)

#### Average daily gain, net energy for gain

ADG is not entered into the model interface for ewes and rams, but is required for sheep feedlot animals.

**For ewes and rams:**

**Eq. 3.3.1‑9**

where

*ADG* Average daily gain (kg head-1 day-1)

*initial\_wt* Initial weight (kg head-1) (**Table 22**, by sheep group)

*final\_wt* Final weight (kg head-1) (**Table 22**, by sheep group)

*#days* Number of days in management period – **includes all days where animals >0 are entered**

**For feedlot sheep (weaned lambs), ewes and rams:**

**Eq. 3.3.1‑10**

IPCC 2019, Eq. 10.7

where

*NEgain* Net energy for gain (MJ head-1 day-1)

*a* Coefficient a (MJ kg-1) (**Table 22**, by sheep group)

*b* Coefficient b (MJ kg-2) (**Table 22**, by sheep group)

*#days* Number of days in management period

#### Ratios of net energy available to digestible energy

**Eq. 3.3.1‑11**

IPCC 2019, Eq. 10.14

where

*REM* Ratio of net energy available in diet for maintenance to digestible energy consumed

*TDN* Percent digestible energy in feed (**Table 26**, by diet)

***TDN* value is to be entered as a percentage (e.g. as 81 not 0.81).**

**Eq. 3.3.1‑12**

IPCC 2019, Eq. 10.15

where

*REG* Ratio of net energy available in diet for gain to digestible energy consumed

#### Gross energy intake

**Eq. 3.3.1‑13**

IPCC 2019, Eq. 10.16

where

*GE* Gross energy intake (MJ head-1 day-1)

#### Enteric CH4 emissions

**Eq. 3.3.1‑14**

IPCC 2019, Eq. 10.21

where

*CH4enteric\_rate* Enteric CH4 emission rate (kg head-1 day-1)

*Ym* CH4 conversion factor (**Table 26**, by sheep group)

*55.65* Energy content of CH4 (MJ kg-1 CH4)

**Eq. 3.3.1‑14**

where

*CH4enteric* Enteric CH4 emissions, by sheep group (kg CH4 day-1)

*#sheep* Number of sheep

### Total enteric CH4 emissions

Emissions should be summed for all relevant management periods and sheep groups.

**Eq. 3.3.2‑1**

IPCC 2019, Eq. 10.20

where

*Total\_CH4enteric* Total enteric CH4 emissions from sheep (kg CH4 year-1)

*CH4enteric* Enteric CH4 emissions (kg CH4)

## Swine, Poultry and other livestock

**Management data are input for each management period. Emissions are calculated on a daily basis.**

**Assumptions:**

* All feed is utilized - waste feed emissions are not accounted for
* All barn manure uses the same handling system
* Manure must be applied at least once per year
* There are no emissions from nursing piglets or other unweaned young
* There are no emissions from chicks or poults

### Enteric CH4 emissions from swine, poultry and other livestock

Daily enteric CH4 calculations should be completed for each animal group within each livestock type.

**Eq. 3.4.1‑1**

IPCC 2019, Eq. 10.19

where

*CH4enteric* Enteric CH4 emissions (kg CH4day-1)

*CH4enteric\_rate* Yearly enteric CH4 emission rate (Vergé et al. (2009) for swine and IPCC (2019) for all other livestock) (**Table 27**)

*365* Number of days in year

### Total enteric CH4 emissions

Emissions should be summed for all management periods and animal groups within each livestock type.

**Eq. 3.4.2‑1**

IPCC 2019, Eq. 10.20

where

*Total\_CH4enteric* Total enteric CH4 emissions (kg CH4 production cycle-1) – in the event that the production cycle equates to 365 days, this total is a yearly total

*CH4enteric* Enteric CH4 emissions (kg CH4), by animal group

## Scaling up of emissions estimates from production cycle to annual values

In Canada, some livestock production systems are typically “all in, all out” systems, where all animals enter and leave the barn at the same time with a number of days between production periods to clean the facilities before the next group of animals arrives. These systems include feedlot cattle (steers and heifers), swine, and poultry production. Therefore, to calculate total annual emissions from a livestock operation where there are multiple production cycles per year, the number of production days per year (excluding non-productive days between production cycles) are considered. Daily emissions estimates are multipled by the total number of production days in a year. In Holos, for each animal group, a single default production cycle (composed of one or more management periods) is provided in the interface, detailing the number of production days in each cycle. A default number of rest days between production cycles is also provided (**Table 28**). For all animal groups not included in **Table 28**, we assume that either their production cycle lasts 365 days (e.g., beef cows and bulls) or that they typically have just a single production cycle per year (e.g., beef calves).

**Please note:** this ‘scaling-up’ is carried out in Holos only for those GHG emissions estimates reported in the Detailed Emission Report on the Results screen (i.e., ‘Enteric CH4’, ‘Manure CH4’, ‘Direct N2O’, ‘Indirect N2O’, ‘Farm energy CO2’, ‘Upstream CO2’ and ‘Subtotal’). All other Holos estimates, including those on the Manure Management report, are for a single production cycle only – if the model user wants to know these estimates for an entire year (365 days), they will need to scale-up these estimates themselves outside of the Holos interface.  
**Please note:** the user can modify the length of individual management periods (and thus the length of the production cycle) and the number of days between production cycles in the model interface.

**Please note:** due a current lack of data regarding sheep production systems in Canada, for these systems the model user will need to scale up themselves from emissions estimates for a single production cycle to the entire year, as for sheep these calculations are not carried out automatically in Holos at this time.

**Eq. 3.4.2‑1**

where

*No.Prod.Cycles*Total number of production cycles per year, by animal group

*No.DaysCycle* Number of days in a single production cycle, by animal group. This is calculated in Holos as the sum of days in all specified management periods for a given animal group; typical values for the average number of days in a single production cycle for certain animal groups are provided, for reference, in **Table 28**

*No.DaysRest* Number of non-production or rest days between production cycles, by animal group, user-specified or default (**Table 28**)

**Eq. 3.4.2‑2**

where

*CH4enteric\_annual* Total enteric CH4 emissions for all production days in a year (kg CH4 year-1), by animal group

*CH4enteric* Enteric CH4 emissions for all animals and all management periods within a single production cycle (kg CH4), by animal group

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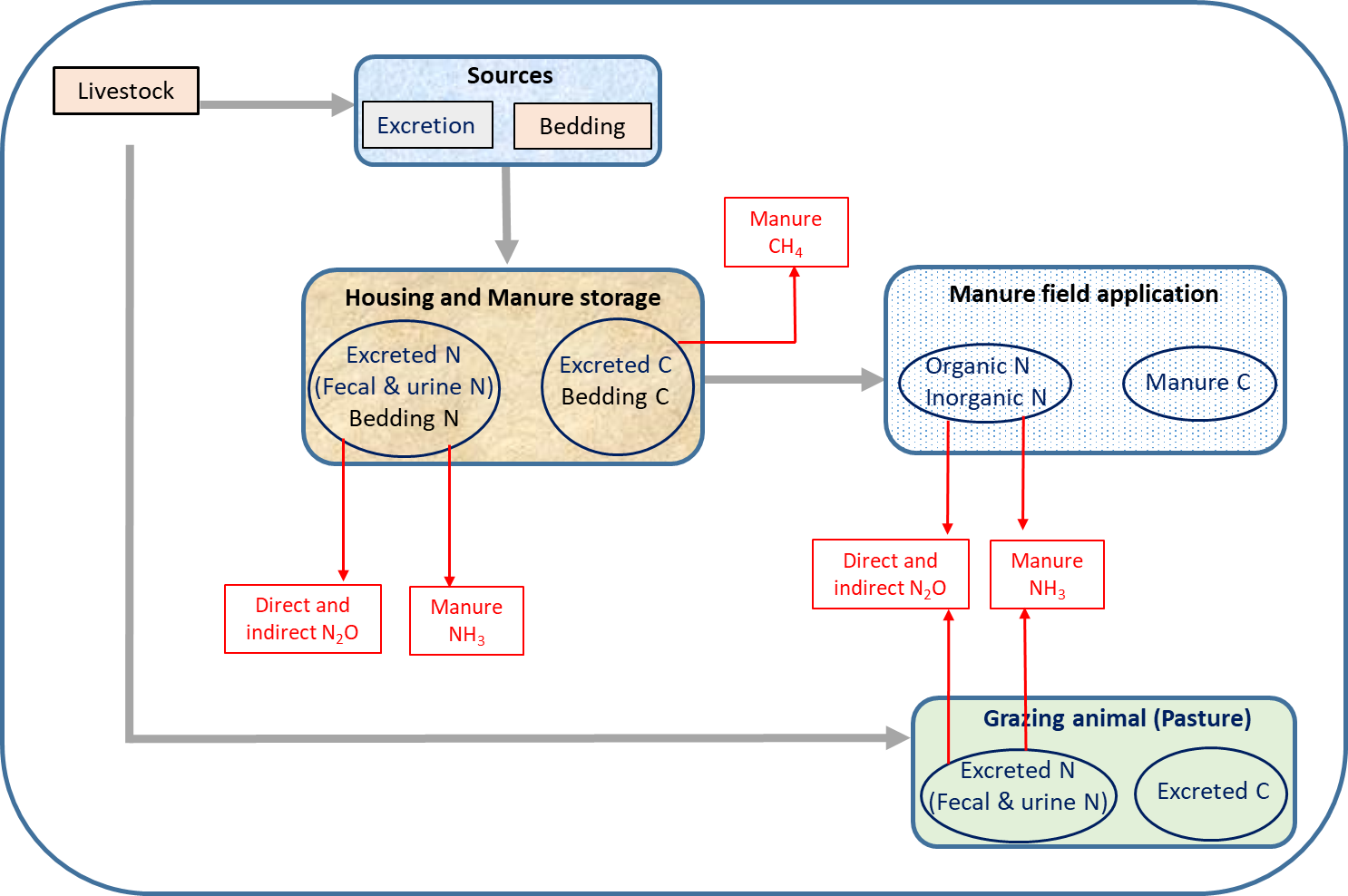
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# Livestock manure: CH4 and N2O emissions from livestock housing and manure storage



**Figure 3.** Carbon (C) and nitrogen (N) flows in manure management for livestock in Canada.   
**Note:** not all C and N flows are applicable to all animal groups.

For a specific livestock housing and manure management system, C and N are sourced from excretion (faeces and urine) and bedding. The amount of C and N remaining after storage is equal to all of the C and N coming into the system minus the losses of C and N during the housing and storage stages (due to CH4 emissions, direct N2O emissions and indirect N2O emissions due to NH3 volatilization and leaching). In Canada, a variety of housing and manure management systems exist for each of the livestock types considered in Holos. An overview of these systems for each livestock type is provided below and a breakdown of the percentage of total manure produced by each livestock type managed in different manure management systems is provided in **Table 29**.

**As for the estimates of enteric CH4 emissions, for those animal groups that have more than one production cycle per year, all estimates per production cycle are “scaled-up” to annual estimates using the approach described in section 3.5.**

**Beef cattle:** In Western Canada (except BC), most cattle are reared on pasture and fattened to market weight in feedlots. Pasture and feedlots are utilized year-round but in winter months enclosed areas such as open barns, sheds and drylots are used in cow-calf operations to provide animals with protection from the wind. More than 90% of the manure from beef housing is stored in solid form in western Canada (Sheppard and Bittman, 2012) via stockpiling (manure placed in a heap without turning, minimizing oxygen supply and the rate of decomposition) or composting (where the manure heap is turned multiple times to accelerate decomposition of organic compounds). In a survey of beef cattle production systems in western Canada, roughly 30% of the systems stored manure as compost, while the remaining 70% stored manure in undisturbed stockpiles (Sheppard and Bittman, 2012).

**Dairy cattle:** In Canada, according to the National Dairy Study (University of Guelph, 2015), based on data available from 10,901 farms, 68.3% of these are tie-stall barns and 31.7% are loose housing barns. Predominant housing types for dairy cattle vary from province to province, with loose housing more prevalent in Western Canada (67.5% in MB to 98.6% in BC) and the Atlantic Provinces (54.6% in NB to 77.8% in NFL), while tie-stall barns dominated in ON (62.2%) and QC (89.3%). The latter two provinces account for 68% of total national milk production (Sep 2014-Aug 2015). In tie-stall barns, cows can stand up and lie down but not turn around, and are thethered with food and water in front of them; they are milked in this position. In free-stall barns, animals can move about in the passage or exercise areas and enter into comfort stalls or resting areas whenever they choose. In loose housing barns, there are no stalls and dairy cattle roam about the barn. Manure and urine deposits should be cleaned from stalls and alleys twice daily. Dairy manure management systems are as reported in Chai et al. (2016), originally identified from the Livestock Farm Practices Survey (LFPS) (Dairy Farmers of Ontario, 2007; Sheppard et al., 2011a,b). From these, feed and manure handling information, estimates of NH3 emissions from lactating cows, dry cows, replacement heifers, calves (< 1 year), and breeding bulls were developed. The dairy housing systems considered were: tie-stall barns, free-stall barns, milking parlours, yards/exercise lots and pasture. Dairy manure is stored in both solid and liquid forms. The manure storage systems considered for solid manure were solid stockpiled and solid composted, and for liquid manure were tank, slurry pit, and lagoon/earthen storage. TAN-based emission factors (EFs, kg (NH3-N) (kg TAN)-1) were developed for each handling system. Manure excreted in barns (tie-stall, free-stall), exercise lots/fields, milking parlours/holding areas, and standing yards was defined as confined housing manure for estimating the initial NH3 emissions from newly excreted manure. Confined housing manure is stored (manure storage stage) and then applied on land (land application stage). If the manure was deep bedded (solid manure with bedding) or stored in a slurry pit under the barn, the emission from the housing stage (fresh manure) and storage stage (old manure) was calculated separately. Manure excreted on pastures was defined as pasture manure or grazing manure.

**Sheep:** In Canada in 2020, there were approximately 1.014 million sheep and lambs, mainly in Saskatchewan (10.6%), Alberta (18.3%), Québec (22.2%) and Ontario (32%) (Statistics Canada, 2021). Sheep in Canada are raised in different systems, including confinement, extensive, dairy, feedlots and hybrid operations that use both outdoor rearing and some housing (NFACC, 2013a). The type of housing will affect the manure management system employed on an operation. In confined and drylot operations, manure is typically managed in a solid system where suitable bedding materials can include straw, wood shavings, paper products, peat and hemp and the recommended bedding application rate is 0.45-0.68 kg bedding head-1 day-1 (Canadian Sheep Federation, 2011). The choice of bedding material can vary from operation to operation, for example, in Manitoba, intensive or confined sheep operations generally use a straw-based manure management system (Province of Manitoba, 2021).

**Swine:** In Holos, swine production systems fall into one of four types, characterized based on dominant production practices: 1) farrow-to-wean - operations that house sows, gilts and possibly boars; these operations maintain the breeding stock but sell piglets to iso-wean or grower-to-finish operations; 2) iso-wean: (isolated wean) operations or ‘nursery barns’ – operations that house piglets that have been weaned at ~18-28 days old (21 days used as default); these animals are kept in isolation from sows and larger hogs to prevent disease transmission. Hogs typically spend 5-8 weeks in a nursery barn, although it can be as little as 2 weeks; 3) grower-to-finish – operations that house feeder hogs until they are marketed at ~110-130 kg live weight; these operations do not keep breeding animals but purchase their pigs from weaner operations; and 4) farrow-to-finish operations – these operations keep and mate sows, farrow litters and raise piglets to market weight. Liquid manure management systems dominate in the swine sector, with 97% of all swine manure produced managed in this form (**Table 29**). Swine manure management systems considered in the Holos model include solid manure (composted in-vessel), and liquid manure (liquid/slurry with or without a natural crust cover, liquid/slurry with solid cover, deep pit, and anaerobic digestion). In swine housing systems, bedding materials can include straw, wood shavings, sawdust or other materials.

**Poultry (chickens and turkeys):** In Canada, chickens for meat and egg production are kept in different housing systems, depending on the stage of production and the desired end product. Multiplier breeder operations house both male and female adult birds managed to produce eggs; multiplier hatcheries receive fertile eggs from multiplier breeder farms, hatch them, and deliver day old chicks to pullet farms or pullet barns on egg-laying operations (female chicks only) or to meat production operations (male and female chicks); pullet farms/barns raise female chicks to egg-laying age; meat producing or broiler operations raise day old chicks to market weight; and egg-laying operations house adult hens for egg production. In turkey production, multiplier breeder and hatchery operations provide day old poults to meat producing operations where the birds are raised to market weight, with males and females typically housed separately throughout their entire life cycle. In Canada, turkey flocks are mainly kept in indoor barn systems on a concrete floor (87.5%) with bedding provided, with the most common litter types provided being wood shavings (47% of respondents) and straw (41% of producers) (van Staaveren et al., 2020). Poultry barns generally have litter floors. Most poultry manure produced in Canada (92%) is managed in solid systems and 7% in liquid form (**Table 29**). Currently, in Holos, only solid poultry manure (with or without litter) is considered. Suitable examples of bedding for poultry are wood shavings and chopped straw (Chicken Farmers of Canada, 2018).

**Horses:** In Canada, horses are used predominantly for sport and recreation, and donkeys are used primarily for companionship (MacMillan et al., 2020). In 2021, there were 189,943 equines in Canada (Statistics Canada, 2022). Most of these animals were distributed across BC, the Prairie provinces, and Ontario. Equines can be housed indoors or outdoors. Indoor housing options include tie stalls, box stalls, or group housing and these must allow sufficient space for the horse to move, lie down, etc. (NFACC, 2013b). Examples of bedding used indoors are straw, shavings, shredded paper, peat moss, and sawdust (NFACC, 2013b). Outdoor housing options include confined paddocks or pastures with extensive grazing systems. A horse’s diet should consist mainly of good quality hay, pasture, or grass, and they should be fed a ration of 60-70% grain at least twice a day. Foaling can happen in any housing type. In terms of manure management, a 450 kg adult horse produces around 23 kg of manure per day, not including bedding (derived from Hofmann and Beaulieu, 2006). In Canada, horse manure is commonly stockpiled, composted, or placed directly on the soil creating large, shallow piles. As with many other animal groups, for horses not grazing on pasture, the most common bedding types are straw and wood shavings (Molnar and Wright, 2006).

**Goats**: According to the 2021 Census of Agriculture, there were approximately 253,278 goats in Canada, mainly in Ontario (58.5%), Quebec (12.8%), and Alberta (13.2%) (Statistics Canada, 2022). Goats can be raised for meat, dairy, fibre, or skin products. Goats are typically managed on pastures or in enclosed systems and fed a diet of grains, dry roughage, and forages (Nova Scotia Department of Agriculture, n.d.). Rotational grazing is recommended for raising goats on pasture. Loose housing is the most common type of enclosed housing system, though individual stalls are also used (Nova Scotia Department of Agriculture, n.d.). Goat pen floors can be slatted, which does not require bedding, or made out of wood, concrete, soil, gravel, metal, or plastic (Canadian Agri-Food Research Council, 2003). When bedding is required, typical materials include straw, wood shavings, and peat moss and bedding application rates vary from farm to farm, depending on barn design, goat stocking density, and the feeding and watering system used (Doris, n.d.). According to the Canadian National Goat Federation, if a manure pack system is used, fresh bedding must be added as needed to keep the surface as dry as possible, or barns should be cleaned out regularly. Adult goats produce approximately 3 kg of manure per animal per day (derived from Hofmann and Beaulieu, 2006), and this manure can be applied on pasture fields or on crop yielding fields as mulch, composted, or stored (stockpiled) (Bauman, 2016).

**Camelids**: Llamas and alpacas are members of the camelid family. In Canada, there were an estimated 12,600 camelids in 2021 (Statistics Canada, 2022). The majority of Canadian llamas and alpacas are in Alberta and British Columbia in small scale operations, with an average of 8 to 10 animals per herd, but numbers in Ontario are growing (Farm & Food Care Ontario, 2016). These animals are popular in Canada for their fibre (Farm & Food Care Ontario, 2016), for shows, promotions, and general entertainment (Alpaca Livestock Producers and Cooperators Association, 2021). Camelids are very social animals and are typically housed in groups outdoors, with a three-sided enclosure for protection from wind and rain, and an enclosed shed in case of extreme cold (Farm & Food Care Ontario, 2016). These animals graze on pasture and do well in marginal lands or rough terrain. They eat 1-2% of their body weight in hay or grass and 1 pound of supplement per day. Both llamas and alpacas are bred naturally and produce only one offspring (Farm & Food Care Ontario, 2016). Camelids produce pelletized faeces and can control the moisture content of their faeces and concentration of their urine, reducing excretion of vital fluids in case of heat stress (Fowler and Bravo, 2010). Camelid manure can be used as fertilizer, but if there is concern that parasite ova will be spread with the manure, it is recommended that the pellets be dried, exposed to sunlight, and ground before spreading (Fowler and Bravo, 2010). Wood shavings, sawdust, and straw can be used for bedding.

**Bison**: There were approximately 119,314 bison in Canada in 2021, mainly in Alberta and Saskatchewan (Statistics Canada, 2022), where they are raised primarily for meat. Bison are generalist foragers (Rioja-Lang et al., 2019), and their diets include mainly grasses and sedges, though they occasionally consume berries and lichens (Panza, 2020). These animals are generally managed on pastures or ranges with well-drained resting areas and with supplementary feeding areas for wintering, calving, or finishing (NFACC, 2017). Bison are extremely well adapted to the winter and do not typically require bedding or enclosed sheds. Estimates for manure production include 36.8 kg (derived from Hofmann and Beaulieu, 2006) per head per day, usually deposited on pasture.

**Deer and Elk**: Deer and elk are members of the Cervidae family, and are farmed mainly in Alberta and Saskatchewan (Farm & Food Care Ontario, 2016). There were a total of 29,655 farmed elk and deer in Canada in 2021 (Statistics Canada, 2022). Deer are farmed for the sale of live animals, meat (venison), their velvet antlers, skin (sold as leather), or for recreational purposes (Canadian AgriFood Research Council, 1996). These animals are ruminant herbivores, typically raised outdoors on native or seeded pasture with natural or artificial shelter (such as trees or enclosed pens) to protect them from the elements. If raised outdoors, rotational grazing is encouraged to maintain pasture productivity and control parasites (Canadian AgriFood Research Council, 1996). In the winter good quality, high energy feeds, such as grains, pellets, or stored forage should be provided because metabolic activity and food intake decreases in the colder months (Canadian AgriFood Research Council, 1996).

## Manure carbon and CH4 emissions from livestock manure

(by A.W. Alemu, S.J. Pogue, D. Beaulieu and P. Mantle)

Manure (faeces + urine) from livestock production systems emits CH4 during the housing and manure storage stages. Carbon in the manure is lost as CH4-C during these stages and the remaining C is moved to the field during manure application. As such, manure C transported from storage to the field equals total manure C (faecal C + bedding C) minus C losses through CH4 emissions during housing and storage.

### Manure carbon

The C content of stored manure is a function of C coming from faecal excreta (undigested C, *Cexcretion*) and added bedding materials (*Cbedding*), if bedding is used.

#### Faecal carbon

For beef cattle, dairy cattle and swine, the amount of C excreted through faeces is calculated as a function of the amount of feed consumed by the animal, the C content of the feed and feed digestibility. Daily C excretion rates (*Cexcretion\_rate)* are calculated for beef and dairy cattle and swine based on dietary information. For sheep, poultry and other livestock, *Cexcretion\_rate* is calculated based on default *Ccontent* (% wet weight) values for manure “as excreted” (**Table 6**) and default values for the volume of manure produced daily by each animal (**Table 29**). **Note:** these equations are also applied to grazing animals on pasture.

**For beef cattle and dairy cattle (including calves):**

**Eq. 4.1.1‑1**

where

*Cexcretion\_rate* C excreted (kg head-1 day-1)

*GEI* Gross energy intake (MJ head-1 day-1)

*18.45* Conversion factor for gross energy per kg DM intake (MJ kg -1)

*Cfeed* C concentration of feed (kg kg-1 DM) (see box below)

*Cdigestibility* Digestibility of C in feed (kg kg-1 DM) (see box below)

Holos V4 will use the following constant values for all feed types for beef cattle and dairy cattle:

*Cfeed* 0.45 kg kg-1 DM for mixed pasture (Baron et al. 2002)

*Cdigestibility* 0.61 kg kg-1 DM (Baron et al. 2002)

**For swine:**

**Eq. 4.1.1‑2**

where

*DMI* Daily DMI (kg head-1 day-1), by swine group (**Table 33**)

Holos V4 will use the following constant values for all feed types for swine:

*Cfeed* 0.45 kg kg-1 DM (Baron et al. 2002)

*Cdigestibility*1 0.88 kg kg-1 DM (Jarret et al., 2011; Jorgensen et al., 2013)

1 *Cdigestibility* is an average of the following values: 84.6% (from Jorgensen et al. (2013) based on swine diets in Denmark), 89.91% and 89.55% (from Jarret et al. (2011) for high and low protein swine diets, respectively).

**For sheep, poultry and other livestock:**

**Eq. 4.1.1‑3**

where

*Manureexcreted\_rate*Volume of manure excreted daily (kg head-1), by animal group (**Table 29**)

*Ccontent* C content of “as excreted” manure (% wet weight), by livestock type (**Table 6**). **Note:** the *Ccontent* value for “Manure (urine + feces) deposited on pasture” or “Pasture/range/paddock” should be used

**For all animal groups:**

**Eq. 4.1.1‑4**

where

*Cexcretion*  Amount of C excreted (kg C day-1), by animal group

*#animals* Number of animals

**Eq. 4.1.1‑5**

where

*Total\_Cexcretion*  Total C excreted (kg C day-1), by livestock type

#### Bedding carbon

In beef cattle production systems, bedding materials are typically sourced from either cereal straw or wood-chips. Default bedding application rates are calculated from published literature (Olson et al., 2006; Larney et al., 2008; Chai et al., 2014). For beef cattle, straw bedding application rates of 1.5 and 3.5 kg head-1 day-1 are used for the feedlot and barn, respectively, and for wood-chip bedding, values of 3.6 and 5.0 kg head-1 day-1 are used for the feedlot and barn, respectively (**Table 30**). In western Canada, 98% of beef farms use straw bedding for housed animals (Sheppard and Bittman, 2012). For dairy cattle, bedding types can include sand, separated manure solids, long and chopped straw, shavings and sawdust. Due to a lack of data, Chai et al. (2016) assumed that chopped straw was used for dairy cattle (0.7 kg animal-1 day-1, Rotz et al., 2013), with a N content of 0.0057 kg N kg-1 (Larney et al., 2008), and that there was no difference between free-stall and tie-stall barns. Thus, additional bedding application rates and C and N concentrations for other bedding types and for other animal groups were derived, where available, from the literature (**Table 30**).

Alternatively, the user can use the “Bedding Application Calculator” to estimate the bedding application rate by entering data on the total number of bales used, average bale weight, the number of days animals spend in the housing type and the number of animals (**Eq. 11.2.2‑1**, **Eq. 11.2.2‑2** and **Eq. 11.2.2‑3**).

While calculating the amount of C and N in manure from beef and dairy calves (and other livestock young), double-counting of bedding C and N needs to be avoided. Calves are managed with cows and the amount of C (*Cbedding*) and N (*Nbedding*) sourced from their bedding material is assumed to be zero. Bedding material applied for beef and dairy cows accounts for calves also.

**For all animal groups**

**Eq. 4.1.1‑6**

where

*Cbedding\_rate* Rate of C added from bedding material (kg head-1 day-1); this value is assumed to be zero for all livestock young

*Bedding\_rate* Rate of bedding material added (kg head-1 day-1, **Table 30**)

*Bedding\_C* C concentration of bedding material (kg C kg-1 DM, **Table 30**)

*MoistureContentbedding* Moisture content of bedding material (%, **Table 30**)

**Eq. 4.1.1‑7**

where

*Cbedding A*mount of C added from bedding materials (kg C day-1), by animal group

*#animals* Number of animals

#### Total manure carbon

**For all livestock:**

**Eq. 4.1.1‑8**

where

*Cmanure* Amount of C added from faeces and bedding materials (kg C day-1), by animal group

**Eq. 4.1.1‑9**

where

*Total\_Cmanure* Total amount of C added from faeces and bedding materials (kg C year-1), by livestock type

### CH4 emissions from solid manure

Emissions of CH4 from solid manure produced by all animal groups are based on the amount of volatile solids (VS) excreted in manure. For beef and dairy cattle, sheep and swine, daily VS production for each animal group is estimated based on gross energy intake, total digestible nutrients in feed, and the ash content of feed. For chickens, goats, llamas and alpacas, horses, mules and bison, default IPCC VS excretion rates are used (**Table 34**).For each of these groups, default IPCC (2019) CH4 conversion factors are used (**Table 36**). For all other livestock groups for which no VS excretion data are available (i.e., turkeys, ducks, geese, deer and elk), a Tier 1 approach is used that employes default IPCC (2019) CH4 emission rates. Manure CH4 calculations for solid manure systems should be completed for each animal group and for each manure management system on a daily basis. **Note:** these equations are also applied to grazing animals on pasture.

#### Volatile solids in solid manure for all animal groups

**For beef cattle, dairy cattle and sheep:**

**Eq. 4.1.2‑1**

IPCC 2019, Eq. 10.24

where

*VS* Volatile solids excreted (kg head-1 day-1), by animal group

*GEI* Gross energy intake (MJ head-1 day-1)

*TDN* Percent total digestible nutrients in feed (**Table 18**, by diet)

*UE* Urinary energy expressed as a fraction of GEI. This value is 0.04 for all ruminants, but is reduced to 0.02 for ruminants fed with 85% or more grain in the diet

*Ash* Ash content of feed (%), calculated as a percentage of the DM feed intake, based on the ash content of the diet ingredients

*18.45* Conversion factor for gross energy per kg of DM (MJ kg-1)

**Note:** for beef calves on a milk-only diet, VS is estimated as: ***VS = 7.6/1000 \* Weight***; for dairy calves on a milk-only diet, the VS is estimated as: ***VS = 9.3/1000 \* Weight***. For all beef and dairy calves on a partial or full forage diet, **Eq. 4.1.2‑1** is used, based on IPCC (2019) default VS excretion rates for dairy and non-dairy cattle.

***TDN* value is to be entered as a percentage (e.g. as 81 not 0.81).**

**For swine:**

**Eq. 4.1.2‑2**

Greenhouse Gas System Pork Protocol 2006

where

*VSadjusted* Adjusted value for volatile solids excreted (kg head-1 day-1), by animal group

*VSexcretion* Volatile solid excretion (kg kg-1) (**Table 31**, by pig group and province)

*VSadjustment* Volatile solid adjustment factor (kg kg-1) (**Table 32**, by diet)  
**Note:** the VS adjustment factor used in Holos for all diets is currently 1, as we work to update the linkages between the *VSadjustment* values in **Table 32** and the Holos default swine diets

**Eq. 4.1.2‑3**

Greenhouse Gas System Pork Protocol 2006

where

*VS*Volatile solids excreted (kg head-1 day-1), by animal group

*feed\_intake* Feed intake (kg head-1 day-1), by swine group (**Table 33**)

**For chickens, goats, llamas and alpacas, horses, mules and bison:**

Default daily VS excretion rates were derived from default IPCC (2019) data and default live animal weights from ECCC (2022) (**Table 34**).

#### CH4 emissions from solid manure

**For beef cattle, dairy cattle, sheep, swine, chickens, goats, llamas and alpacas, horses, mules and bison:**

**Eq. 4.1.2‑4**

IPCC 2019, Eq. 10.23

where

*CH4manure\_rate*Manure CH4 emission rate (kg head-1 day-1), by animal group

*VS* Volatile solids (kg head-1 day-1) – values for beef cattle, dairy cattle and sheep solid manure from **Eq. 4.1.2‑1**; values for for swine solid manure from **Eq. 4.1.2‑3**; values for poultry and other livestock solid manure from **Table 34**

*Bo* Methane producing capacity (m3 CH4 kg-1 VS) by livestock type (**Table 35**)

*MCF*Methane conversion factor (**Table 36**, by livestock type and manure handling system)

*0.67* Conversion factor from volume to mass (kg m-3)

For **turkeys, ducks and geese, and deer and elk**, default IPCC (2019) *CH4manure\_rate* values are provided in **Table 38**.

**For all animal groups:**

**Eq. 4.1.2‑5**

IPCC 2019

where

*CH4manure* Manure CH4 emissions (kg CH4 day-1), by animal group

*CH4manure\_rate* Manure CH4 emissions (kg CH4 head-1 day-1)

*#animals* Number of animals

### CH4 emissions from liquid dairy cattle and swine manure

Methane emissions from liquid manure relate to dairy cattle and swine production systems. For dairy and swine liquid manure systems (with and without a natural or solid cover), default MCFs are not used, but instead are estimated using the methodology outlined in Vergé et al. (2006), based on Mangino et al. (2001). Based on the user’s choice for the timing of manure application, daily MCF values are calculated as well as a yearly MCF. The user can override this MCF and manure CH4 calculations will revert to those of solid manure. Manure CH4 calculations for liquid manure systems should be completed for each dairy cattle group, for each swine group and for each manure management system on a daily basis.

**Eq. 4.1.3‑1**

where

*T2* Air temperature (K)

*Temp* Average temperature, by day and location from NASA (°C)

*273.15* Conversion from degrees Celsius to degrees Kelvin

**Note:** If Temp< or = 0 °C, use 1 °C.

**Van Hoff-Arrhenius equation to forecast performance of biological reactions:**

**Eq. 4.1.3‑2**

where

*f* Climate factor

*T*1  303.16 K

*T*2 Air temperature (K)

*E* Activation energy constant (15,175 cal mol-1)

*R* Ideal gas constant (1.987 cal K mol-1)

**Eq. 4.1.3‑3**

where

*VSproduced*  Total volatile solids produced by all animals in a day (kg), by animal group

*VS* Volatile solids (kg head-1 day-1), by animal group, calculated using **Eq. 4.1.2‑1** for dairy cattle and **Eq. 4.1.2‑3** for swine

*#animals*  Number of animals

**Eq. 4.1.3‑4**

where

*VSloaded* Daily volatile solids loaded into system (kg day-1)

*MDP* Management and design practice factor (default = 0.45, one-time data input)

**Eq. 4.1.3‑5**

where

*VSavailable*  Daily volatile solids available for conversion to CH4 (kg VS)

*VSloaded(d)*  Daily volatile solids loaded into system on the current day, *d* (kg VS)

*VSavailable(d-1)*  Daily volatile solids available on the previous day, *d-1* (kg VS)

*VSconsumed(d-1)*  Daily volatile solids consumed on the previous day, *d-1* (kg VS) – from **Eq. 4.1.3‑7**

**Note: On days that the liquid manure is emptied, there is no carryover.** **Therefore,**

**Eq. 4.1.3‑6**

**Eq. 4.1.3‑7**

where

*VSconsumed*  Daily volatile solids consumed (kg VS day-1)

**Eq. 4.1.3‑8**

where

*CH4manure\_daily* Daily CH4 emissions (kg day-1)

*Bo* CH4 producing capacity (**Table 35**)

*0.67* Conversion factor from volume to mass (kg m-3)

**Daily emissions for covered systems:**

**Eq. 4.1.3‑9**

where

*CH4manure\_daily*(covered) Daily CH4 emissions for a covered system (kg day-1)

*EmissionReductioncover* Reduction in CH4 emissions from liquid manure system due to cover. This assumes a 40% reduction in CH4 for natural crust covered systems[[9]](#footnote-10) and a 25% reduction in CH4 for systems with a solid cover[[10]](#footnote-11) (IPCC 2019, Table 10.17 footnotes).

**Eq. 4.1.3‑10**

where

*CH4manure*  Manure CH4 emissions (kg CH4 year-1)

**Note: Use *CH4manure\_daily(uncovered)* for an uncovered system.**

**Eq. 4.1.3‑11**

where

*VSproduced\_yearly* Volatile solids produced yearly (kg VS)

**Eq. 4.1.3‑12**

where

*MCF* Methane conversion factor

**Note: If the user overrides the calculated MCF, use Eq. 4.1.2‑4** and **Eq. 4.1.2‑5 (as for solid manure)**

#### Carbon loss as manure methane for all animal groups

**Eq. 4.1.3‑13**

where

*CmanureCH4* C lost as CH4 during manure management (kg C day-1), by animal group

*12/16* Conversion from CH4 to C

#### Flow of manure C from housing to manure storage systems

**To estimate the flow of manure C from housing to manure storage systems on a daily basis, for all livestock types:**

**Eq. 4.1.3‑14**

where

*Cflowstorage* Total amount of C flowing into storage each day (minus housing CH4 emissions) (kg C day-1), by animal group and manure management system

**Eq. 4.1.3‑15**

where

*Cstorage(t)* Amount of C in stored manure on day *t* (kg C), by animal group and manure management system

*Cstorage(t-1)* Amount of C in stored manure on day *t-1* (kg C), by animal group and manure management system

*Cflowstorage(t)* Amount of C flowing into storage from manure on day *t* (kg C day-1), by animal group and manure management system

**Eq. 4.1.3‑16**

where

*Total\_Cstorage* Total amount of C in stored manure available on a given day for land-application, addition to an AD system or export (kg C), by livestock type and manure management system

*Cstorage* Amount of C in stored manure on a given day (kg C), by animal group and management system, calculated using **Eq. 4.1.3‑15**

#### Removal of manure carbon from storage before the end of the year/simulation period

If manure is removed from the storage system for application to land, addition to an anaerobic digestion (AD) system, or export from the farm before the end of the year or simulation period, the amount of manure C remaining in the storage “tank” on the day following removal must be reduced by the relevant amount.

**Eq. 4.1.3‑17**

where

*Total\_Cstorage(t)* Amount of C in stored manure (kg C) on day *t* (day following manure removal), by livestock type and manure management system

*Total\_Cstorage(t-1)* Total amount of C in stored manure (kg C) on day *t-1* (day of removal, prior to removal), by livestock type and manure management system

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage on day *t-1* (kg), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on the day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

## **Manure nitrogen and direct N2O emissions from livestock manure in housing**

(by A.W. Alemu, S.J. Pogue, D. Beaulieu and P. Mantle)

Direct daily N2O emissions occur from livestock manure (urine + faeces) deposited in housing via combined nitrification and denitrification of N contained in the manure. The direct N2O emission rate (kg N2O head-1 day-1) depends on the amount of total N excreted by the animal in urine and faeces (*Nexcretion\_rate*) and default IPCC N2O emission factors (*EFdirect*) specific to each animal group, manure type and housing type (**Table 36**). Direct N2O emissions are estimated on a daily basis for each animal group and each housing and manure management system. For all animal groups, default IPCC (2019) *EFdirect* values for direct N2O emissions were used (**Table 36**).

### Total manure nitrogen

#### Total nitrogen excreted in urine and faeces

For beef and dairy cattle, sheep and swine, an IPCC Tier 2 approach is used, with a country-specific *Nexcretion\_rate* (kg N head-1 day-1 in faeces and urine) estimated based on animal feed intake, diet composition (crude protein, CP) and N utilization or retention for different animal groups. For cattle, this approach uses a combination of IPCC (2019) Tier 2 equations and information in the Nutrient Requirements of Beef Cattle (NASEM, 2016) and the Nutrient Requirements of Dairy Cattle (National Research Council, 2001). The fraction of N excreted in animal urine (urinary-N or urea-N) is generally referred to as excreted total ammonical N (TAN – important in the estimation of indirect N losses via ammonia (NH3) volatilization for beef cattle and dairy cattle, see **section 4.3**) and the remaining fraction is faecal N (organic N).

For swine, a combination of data and equations from IPCC (2019), the Greenhouse Gas System Pork Protocol (2006) and Vergé et al. (2009), together with dietary data provided by D. Beaulieu (University of Saskatchewan) are used for these calculations. For some poultry groups (pullets, broilers and layers), an IPCC Tier 2 approach to estimate *Nexcretion\_rate* is also employed, using Canada-specific data on protein intake and retention, together with IPCC (2019) equations.

For other livestock (goats, llamas and alpacas, deer and elk, horses, mules, bison), an IPCC Tier 1 approach is used, which estimates *Nexcretion\_rate* based on default N excretion values and animal liveweight data from IPCC (2019) and ECCC (2022) (**Table 42**).

##### For beef and dairy cattle

**Eq. 4.2.1‑1**

Derived from IPCC 2019, Eq. 10.32

where

*PI* Protein intake (kg head-1 day-1)

*GEI* Gross energy intake (MJ head-1 day-1)

*18.45* Conversion factor for gross energy per kg of DM (MJ kg-1)

*CP* Crude protein content (kg kg-1) (**Table 18**, by diet)

**For pregnant beef and dairy cows only:**

**Eq. 4.2.1‑2**

where

*PRfetal* Protein retained for pregnancy (kg head-1 day-1)

*5* Protein retained per pregnancy (kg head-1) (NASEM 2016)

*365* Number of days in a year

This equation prorates pregnancy protein retained over the year.

**For lactating beef and dairy cows only (use only when cows are lactating):**

**Eq. 4.2.1‑3**

Derived from IPCC 2019, Eq. 10.33

where

*PRlactation* Protein retained for lactation (kg head-1 day-1)

*milk\_production* Milk production for beef or dairy cows (kg head-1 day-1 )

*milk\_protein* Protein content of milk (kg kg-1)

*#calves* Number of beef or dairy calves

*#cows* Number of beef or dairy cows

**#calves/#cows adjusts for cows without calves and averages protein retained for lactation over all individuals.   
Note: for dairy cows, “#calves/# cows” is always equal to 1, as dairy cows are lactating (during lactating periods) even if no calves are present.**

Holos V4 will use the following constant values:

*milk\_protein\_beef* 0.0338 (kg kg-1) (Legesse et al. 2016)

*milk\_protein\_dairy* 0.035 (kg kg-1) (National Research Council 2001)

**For growing beef and dairy cattle only - if final weight ≠ initial weight:**

**Eq. 4.2.1‑4**

NASEM 2016

where

*EBW* Empty body weight (kg head-1)

*Weight* Weight (kg head-1)

**For growing beef and dairy cattle only - if final weight ≠ initial weight:**

**Eq. 4.2.1‑5**

NASEM 2016

where

*EBG* Empty body gain (kg head-1 day-1)

*ADG* Average daily gain (kg head-1 day-1)

**If the ADG is user-entered, Holos uses the user-specified value; otherwise, the calculated value is used (estimated based on the start and end weights and the no. of days in the management period).**

**For growing beef and dairy cattle only - if final weight ≠ initial weight:**

**Eq. 4.2.1‑6**

NASEM 2016

where

*RE* Retained energy (Mcal head-1 day-1)

**For growing beef and dairy cattle only - if final weight ≠ initial weight:**

**Eq. 4.2.1‑7**

NASEM 2016

where

*PRgain* Protein retained for gain (kg head-1 day-1)

**Eq. 4.2.1‑8**

Derived from IPCC 2019, Eq. 10.31A

where

*Nexcretion\_rate* N excretion rate (kg head-1 day-1)

*6.25* Conversion from dietary protein to dietary N

*6.38* Conversion from milk protein to milk N

**For calves:**

Note: for milk-fed calves, the Holos calculations consider PImilk and PRmilk only, but for calves fed on a combination of milk and forage, the model considers the PI and PR calculations for both milk and solid feed.

**Eq. 4.2.1‑9**

Janzen et al. 2006

*where*

*PIsolid* Beef calf protein intake from solid food (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), calculated according to **Eq. 3.1.2‑2** for beef calves

*CP* Crude protein content (kg kg-1) (**Table 18**, by diet)

**Eq. 4.2.1‑10**

*where*

*PImilk* Beef calf protein intake from milk (kg head-1 day-1)

*milk\_production* Milk production (kg head-1 day-1 )

*milk\_protein* Protein content of milk (kg kg-1)

**Eq. 4.2.1‑11**

*where*

*PI* Beef calf protein intake (kg head-1 day-1)

**Eq. 4.2.1‑12**

*Where*

*PRsolid* Beef calf protein retained from solid feed (kg head-1 day-1)

**Eq. 4.2.1‑13**

*where*

*PRmilk* Beef calf protein retained from milk (kg head-1 day-1)

**Eq. 4.2.1‑14**

*where*

*PR* Beef calf protein retained (kg head-1 day-1)

**Eq. 4.2.1‑15**

Derived from IPCC 2019, Eq. 10.31A

where

*Nexcretion\_rate* N excretion rate for beef calves (kg head-1 day-1)

*6.25* Conversion from dietary protein to dietary N

For dairy calves, a default *Nexcretion\_rate* of 0.078 is used. This value is based on an average calf weight of 130 kg (40 kg birth weight, 220 kg slaughter weight) and a default N excretion value for dairy cattle of 0.6 kg N (1,000 kg animal mass)-1 day-1 (IPCC 2019, Table 10.19).

##### For sheep

**Eq. 4.2.1‑16**

Derived from IPCC 2019, Eq. 10.32

where

*PI* Protein intake (kg head-1 day-1)

*GEI* Gross energy intake (MJ head-1 day-1)

*18.45* Conversion factor for gross energy per kg of DM (MJ kg-1)

*CP* Crude protein content (kg kg-1) (**Table 26**, by diet)

**Eq. 4.2.1‑17**

Derived from IPCC 2019, Eq. 10.32

where

*PR*Protein retained (kg (kg PI)-1), default value from IPCC (2019), Table 10.20

**Eq. 4.2.1‑18**

Derived from IPCC 2019, Eq. 10.31

where

*Nexcretion\_rate* N excretion rate (kg head-1 day-1)

*6.25* Conversion from dietary protein to dietary N

##### For swine

**Eq. 4.2.1‑19**

Derived from IPCC 2019, Eq. 10.32A

where

*PI* Protein intake (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1), by swine group (**Table 33**)

*CP* Crude protein content (%), by swine group (**Table 39**)

**For breeding sows (applied to all sow animal groups/management periods and open gilt, gestating gilt and lactating gilt management periods):**

**Eq. 4.2.1‑20**

IPCC 2019, Eq. 10.33A

where

*PRbreedingsow* Protein retained by breeding sows (kg head-1 day-1)

*PRgain* Protein retained in the sow (kg head-1 day-1), calculated using **Eq. 4.2.1‑21**

*PRnursingpiglets* Protein retained in nursing piglets (kg head-1 day-1), calculated using **Eq. 4.2.1‑22**

**Eq. 4.2.1‑21**

IPCC 2019, Eq. 10.33A

where

*FR* Fertility rate of sows (no. litters year-1), calculated as: 365 / (no. days lactating + no. days open + no. days gestating in a single production cycle)

*Skg* Live weight change of sows during gestation (kg head-1), calculated as: end weight – start weight

*350* Total number of days per year sows spend either gestating or lactating (based on a typical gestation period of 114 days, a typical lactation period of 21 days, and a typical open period of 5 days post-wean before the sow is bred again

**Eq. 4.2.1‑22**

IPCC 2019, Eq. 10.33B

where

*PRnursingpiglets* Protein retained in animal (kg head-1 day-1)

*LITSIZE* Litter size (no. piglets), calculated as: no. piglets / (no. gilts + no. sows)

*Wkg* Live weight of piglet at weaning age (kg head-1)

*Ckg* Live weight of piglet at birth (kg head-1)

*0.98* Protein digestibility as a fraction (FAO, 2017 – cited in IPCC (2019))

**Note:** as the amount of protein retained in nursing piglets is accounted for in *PRbreedingsow*, Holos does not calculate a separate PR value for nursing piglets.

**For growing pigs (applied to boars, non-breeding gilts, weaners, growers and finishers):**

For growing pigs, *PRgrowingpigs* is calculated separately for each management period, using the start and end weights for the relevant period and the default *PRgain* value for the appropriate weight range.

**Eq. 4.2.1‑23**

IPCC 2019, Eq. 10.33C

where

*PRgrowingpigs* Protein retained in animal (kg head-1 day-1)

*#days* Number of days the animals spend in the management period

*BWfinal* Live weight of the animal at the end of the stage (kg) for each growth stage/management period

*BWinitial* Live weight of the animal at the beginning of the stage (kg) for each growth stage/management period

*PRgain* Fraction of protein retained at a given BW – this fraction should be calculated for the final BW of the stage, where *PRgain = Ngain \* 6.25* (**Table 40**)

**For all swine groups (except nursing piglets):**

**Eq. 4.2.1‑24**

Derived from IPCC 2019, Eq. 10.31A

where

*Nexcretion\_rate* N excretion rate (kg head-1 day-1)

*6.25* Conversion from dietary protein to dietary N

*Nexcretedadjustment* N excreted adjustment factor (kg kg-1) (**Table 32**, by diet)   
**Note:** the N adjustment factor used in Holos for all diets is currently 1, as we work to update the linkages between the *Nexcretedadjustment* values in **Table 32** and the Holos default swine diets

##### For chickens (pullets, broilers and layers)

For pullets (for egg-laying birds), broilers and layers, an IPCC Tier 2 approach is used to estimate *Nexcretion\_rate*.

**For pullets (for egg-laying birds), broilers (incl. roasters) and layers:**

**Eq. 4.2.1‑25**

Derived from IPCC 2019, Eq. 10.32A

where

*PI* Protein intake (kg head-1 day-1)

*DMI* DM intake (kg head-1 day-1) (**Table 41**, by animal group)

*CP* Crude protein content in dietary DM (% of DM) (**Table 41**, by animal group and diet)

**For layer hens**

**Eq. 4.2.1‑26**

IPCC 2019, Eq. 10.33D

where

*PRlayer* Protein retained in animal (kg head-1 day-1)

*PRLW* Average protein content in live weight (kg protein (kg head)-1). A default value of 0.175 is used (**Table 41**)

*WG* Average daily weight gain (kg head-1 day-1). A default value of 0.0015 kg head-1 day-1 is used (**Table 41**)

*PRegg* Average protein content of eggs (kg protein (kg egg)-1). A default value of 0.12 is used (**Table 41**)

*EGG* Egg mass production (g egg head-1 day-1). A default value of 48.50 g egg head-1 day-1 is used (**Table 41**)

**For pullets (for egg-laying birds) and broilers:**

**Eq. 4.2.1‑27**

IPCC 2019, Eq. 10.33E

where

*PRpullet\_broiler* Protein retained in animal (kg head-1 day-1)

*BWfinal* Live weight of the animal at the end of the production period (kg) (**Table 41**)

*BWinitial* Live weight of the animal at the beginning of the production period (kg) (**Table 41**)

*PRgain* The fraction of protein (kg kg-1) retained per kg body weight gain. A default value of 0.175 kg kg-1 is calculated as 0.028 \* 6.25, where 0.028 kg is the IPCC (2019) default value for the fraction of N retained per kg of body weight gain and 6.25 is the dietary N to dietary protein conversion factor

*production\_period* No. of days in the production period (**Table 41**)

**For pullets, broilers and layers:**

**Eq. 4.2.1‑28**

Derived from IPCC 2019, Eq. 10.31a

where

*Nexcretion\_rate* N excretion rate (kg head-1 day-1)

*6.25* Conversion from dietary protein to dietary N

##### For other livestock

For all other livestock types (turkeys, ducks, geese, goats, llamas and alpacas, deer and elk, horses, mules and bison), default daily *Nexcretion\_rate* (kg head-1 day-1) values are used (**Table 42**). These values are based on ECCC (2022) data for animal live weights (kg) and N excretion rates (kg N (1000 kg animal mass)-1 day-1) from IPCC (2019).

##### For all animal groups

**Eq. 4.2.1‑29**

where

*Nexcretion*  N excreted (kg N day-1), by animal group

*Nexcretion\_rate* N excretion rate (kg head-1 day-1), calculated for beef and dairy cattle, swine, sheep and some poultry groups, or using **Table 42** for turkeys, geese, goats, llamas and alpacas, deer and elk, horses, mules and bison

*#animals* Number of animals

**Eq. 4.2.1‑30**

where

*Total\_Nexcretion*  Total N excreted (kg N day-1), by livestock type

#### Bedding nitrogen

#### The bedding application rate used to calculate the amount bedding C added to manure is used to calculate the amount of bedding N added to manure that is eventually spread on the simulated farm’s fields, added to an AD system or exported from the farm. While calculating the amount of C and N in manure from beef and dairy calves, double-counting of bedding C and N needs to be avoided. Calves are managed with cows and the amount of C (*Cbedding*) and N (*Nbedding*) sourced from bedding material for this group is assumed to be zero, as bedding material applied for beef and dairy cows accounts for calves as well. This also applies to the young of other animal groups (except poultry).

**For all animal groups:**

**Eq. 4.2.1‑31**

where

*Nbedding\_rate* Rate of N added from bedding material (kg N head-1 day-1). For livestock young, *Nbedding\_rate* = 0 as the N in bedding for the young is already accounted for in the N in bedding for cows/ewes/sows, etc.

*Bedding\_rate* Rate of bedding material added (kg head-1 day-1, **Table 30**)

*Bedding\_N* N concentration of bedding material (kg N kg-1 DM, **Table 30**)

*MoistureContentbedding* Moisture content of bedding material (%, **Table 30**)

**Eq. 4.2.1‑32**

where

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group

*#animals* Number of animals

#### Total manure nitrogen

**For all livestock:**

**Eq. 4.2.1‑33**

where

*Nmanure* Amount of N in urine, faeces and bedding materials (kg N day-1), by animal group

**Eq. 4.2.1‑34**

where

*Total\_Nmanure* Total amount of N added from faeces and bedding materials (kg N year-1), by livestock type

### Direct N2O emissions for all animal groups

**Eq. 4.2.2‑1**

Derived from IPCC 2019, Eq. 10.25

where

*N2O-Ndirectmanure\_rate* Direct N2O-N emissions from manure (kg N2O-N head-1 day-1), by animal group

*EFdirect* Emission factor [kg N2O-N (kg N)-1] (**Table 36**, by livestock type and manure handling system)

**Eq. 4.2.2‑2**

where

*N2O-Ndirectmanure* Direct N2O-N emissions from manure (kg N2O-N day-1), by animal group

*#animals* Number of animals

## Indirect N2O emissions from livestock manure during housing and storage

(by A.W. Alemu, S.J. Pogue, D. Beaulieu and P. Mantle)

Compared with Holos V3, Holos V4 includes some new algorithms and approaches for estimating animal N intake, retention and excretion, manure TAN fractions, N transformations (mineralization, immobilization, nitrification and denitrification), and calculations of N2O, NO, and N2 emissions and NO3-N leaching/runoff during manure storage. In addition, some model parameters have been refined (e.g., updated emission factors for liquid manure scraping and flushing) based on U.S. National Air Emissions Monitoring Study (NAEMS) (Bogan et al., 2010; Ramirez-Dorronsoro et al., 2010).

Indirect N2O-N losses from animal housing and manure storage are calculated from N losses through volatilization and leaching/runoff. Volatilization loss is estimated from NH3-N losses. For beef and dairy cattle, a Tier 2 methodology is used to estimate NH3 volatilization losses based on the TAN in cattle manure, using an approach that estimates these losses for different housing and manure storage systems using a TAN mass balance approach. For broilers, layers and turkeys, default values for total uric acid or TAN excreted and fractions of excreted uric acid or ammoniacal N emitted as NH3 from housing and storage are used, based on Canada-specific values from Sheppard et al. (2009a,b). For cattle and poultry, the fraction of excreted and bedding N lost as NH3-N during the housing and storage stages (*Fracvolatilization*) is then estimated for each animal group, and used together with IPCC (2019) default indirect N2O EFs to estimate N2O volatilization losses. For all other livestock, a Tier 1 approach is used that employs IPCC (2019) default *Fracvolatilization* values rather than calculated values, together with the IPCC indirect N2O EFs.

For all animal groups, daily indirect N losses via leaching and runoff from housing and manure storage are estimated using the IPCC Tier 1 approach, which utilizes IPCC (2019) default *Fracleach* and *EFleach* values. The sum of all volatilization and leaching/runoff N2O losses is equal to the total indirect N2O losses for each animal group.

### Manure NH3 volatilization from housing for beef cattle and dairy cattle (including calves)

A mass balance model based on the TAN in animal manure is applied for beef cattle (based on Chai et al., 2014) and dairy cattle (based on Chai et al., 2016). The model was developed to predict NH3 loss from animal housing and manure storage and grazing (where applicable) for each cattle group. This approach requires estimates of TAN excretion together with temperature-adjusted NH3 emission factors (Chai et al. 2014; 2016) for different housing and manure storage systems to produce NH3 emission estimates for each animal group.

For beef cattle, default TAN-based NH3 emission factors (EFs) (kg (NH3-N) (kg TAN)-1) for housing (feedlot, barn, pasture), solid manure storage (stockpiling, composting) and land application (tilled, reduced tillage/untilled) were obtained from Chai et al. (2014) (**Table 43**). Emission factors for the different stages of manure management are adjusted for temperature based on the Q10 (Q10 = 1.5) method (Sheppard and Bittman, 2012), where the NH3 emission rate increases 1.5 fold for every 10 °C increase above the reference temperature (15 °C) and decreases 1.5 fold for every 10 °C decrease below the reference temperature. Beef cattle barns are naturally-ventilated buildings and in naturally-ventilated barns the indoor temperature is assumed to be 2 °C higher than the outside during the cold season, thus the EF is adjusted accordingly. Similarly, the manure (bedding) surface temperature is also assumed to be 2 °C higher than the ambient air temperature following microbial heat generation during storage. Manure excreted on pasture is defined as pasture manure or grazing manure.

For dairy cattle, default TAN-based NH3 EFs (kg (NH3-N) (kg TAN)-1) for housing (tie-stall barns, free-stall barns, milking parlours, yards/exercise lots, pasture), solid manure storage (stockpiling, composting), liquid manure storage (tank, slurry pit, lagoon/earthen storage) and land application (tilled and no-till solid spreading, slurry broadcasting, drop hose banding, shallow injection and deep injection) were obtained from Chai et al. (2016) (**Table 43**). Manure excreted in barns (tie-stall, free-stall), exercise lots/fields, milking parlours/holding areas, and standing yards is defined as confined housing manure for estimating the initial NH3 emissions from newly excreted manure. Confined housing manure is stored (manure storage stage) and then applied on land (land application stage). Manure excreted on pasture is defined as pasture manure or grazing manure.

#### Urinary nitrogen/total ammonical nitrogen (TAN) for beef and dairy cattle (including calves)

The fraction of excreted N in animal urine (*FracurinaryN*) is referred to as excreted TAN and the remaining fraction (faecal N) as organic N. An equation (Dong et al., 2014) is used to estimate TAN fractions as a function of dietary CP content for lactating and non-lactating (dry cows, replacement heifers, calves and bulls) beef and dairy animals. For beef animals, default *FracurinaryN* values are used, as detailed in the box below. For dairy animals, **Eq. 4.3.1‑1** and **Eq. 4.3.1‑2** are used to estimate *FracurinaryN* (Chai et al., 2016).

**For lactating dairy cows:**

**Eq. 4.3.1‑1**

where

*FracurinaryN\_Dairylac* Fraction of excreted N in the urine (urinary-N or urea-N fraction) of lactating dairy cows (kg TAN (kg manure N)-1)

*CP* Crude protein content of diet (kg CP (kg DM)-1)

**For non-lactating dairy animals (calves, dry cows, bulls, replacement heifers):**

**Eq. 4.3.1‑2**

where

*FracurinaryN\_Dairynonlac* Fraction of excreted N in the urine (urinary-N or urea-N fraction) of non-lactating dairy animals (kg TAN (kg manure N)-1)

**Both *FracurinaryN\_Dairylac*and *FracurinaryN\_Dairynonlac*must be between 0 and 1**

**For all beef and dairy cattle:**

**Eq. 4.3.1‑3**

where

*TANexcretion-rate* TAN excretion rate (kg TAN head-1 day-1)

*FracurinaryN* Fraction of N excreted in urine (urinary-N or urea-N fraction), which varies with dietary CP content (kg TAN (kg manure N)-1)

**Eq. 4.3.1‑4**

where

*TANexcretion* TAN excretion (kg TAN day-1), by animal group

*#cattle* Number of beef or dairy cattle

Holos V4 will use the following constant values for beef cattle:

*FracurinaryN\_Beef* 0.4 for diet/feed CP content (kg kg-1 DM) <0.09

*FracurinaryN\_Beef* 0.57 for diet/feed CP content (kg kg-1 DM) ≥0.09 and <0.15

*FracurinaryN\_Beef* 0.61 for diet/feed CP content (kg kg-1 DM) ≥0.15

(Chai et al. 2014; Dong et al. 2014)

#### Faecal nitrogen for beef and dairy cattle (including calves)

The amount of N excreted by beef and dairy cattle through faeces (faecal N) is calculated as the difference between total N excreted (*Nexcretion*) and the N excreted in urine (*TANexcretion*).

**Eq. 4.3.1‑5**

where

*FaecalNexcretion\_rate* Faecal N excretion rate (kg N head-1 day-1)

**Eq. 4.3.1‑6**

where

*FaecalNexcretion* N excreted in faeces (kg N day-1), by animal group

*#cattle* Number of beef or dairy cattle

#### Manure organic nitrogen (ON) for beef and dairy cattle

The total amount of organic N contained in manure is the sum of the faecal N excreted by the animal and the N contained in livestock bedding.

**Eq. 4.3.1‑7**

where

*OrganicNmanure* Daily organic N in excreted manure and bedding (kg N), by animal group

*Nbedding* N in bedding material (kg N), calculated using **Eq. 4.2.1‑31** – this is zero for beef and dairy calves as the N in bedding for these animals is already accounted for in the *NBedding* for beef and dairy cows

#### Manure NH3 volatilization from housing for beef and dairy cattle (including calves)

##### Confined no barn (feedlot) for beef cattle and confined (tie-stall, small and large free-stall, milking parlour, yard/exercise lot) for dairy cattle (including calves)

**Eq. 4.3.1‑8**

where

*ATAfeedlot* Ambient temperature-based adjustments used to correct default NH3 emission factors for confined no barn (feedlot) housing for beef cattle and confined dairy cattle housing systems (tie-stall, free-stall, milking parlour, yard/exercise lot)

*T* Average daily temperature (°C) – for all outdoor housing systems (i.e., confined no barn (feedlot) for beef cattle and yard/exercise lot for dairy cattle, *T* is the ambient outdoor temperature; for all indoor housing systems for dairy cattle (i.e., tie-stall, free-stall and milking parlour), *T* is the ambient temperature inside the barn (Table 63)

**Eq. 4.3.1‑9**

where

*EFconfinednobarn\_adju* Adjusted NH3 emission factor for confined no barn (feedlot) housing for beef cattle (feedlot) and confined dairy cattle housing systems (tie-stall, free-stall, milking parlour, yard/exercise lot) (kg NH3-N kg-1 TAN) (0 ≤ EFadjusted ≤ 1)

*EFconfinednobarn* Default NH3 emission factor for confined no barn (feedlot) housing for beef cattle (feedlot) and confined dairy cattle housing systems (tie-stall, free-stall, milking parlour, yard/exercise lot) (kg NH3-N kg-1 TAN) (**Table 43**)

**Eq. 4.3.1‑10**

where

*NH3\_Nconfinednobarn\_rate* Daily NH3-N emissions from confined no barn (feedlot) housing for beef cattle (feedlot) and confined dairy cattle housing systems (tie-stall, free-stall, milking parlour, yard/exercise lot) (kg NH3-N head-1 day-1)

**Eq. 4.3.1‑11**

where

*NH3\_Nconfinednobarn* Daily NH3-N emissions for confined no barn (feedlot) housing for beef cattle (feedlot) and confined dairy cattle housing systems (tie-stall, free-stall, milking parlour, yard/exercise lot) (kg NH3-N day-1), by animal group

*#cattle* Number of beef or dairy cattle

**Ammonia emissions from housing are calculated on a daily basis.**

##### Housed in barns (beef cattle only, including calves)

Beef cattle barns are naturally-ventilated buildings and in naturally-ventilated barns the indoor temperature is assumed to be 2 oC higher than outside during the cold season, therefore the EF is adjusted accordingly.

**Eq. 4.3.1‑12**

where

*ATAbarn* Ambient temperature-based adjustment used to correct default NH3 emission factors for beef cattle barns

*T* Average daily temperature (°C)

**Eq. 4.3.1‑13**

where

*EFbarn\_adju* Adjusted NH3 emission factor for beef barns ((kg NH3-N kg-1 TAN ) (0 ≤ EFadjusted (b,m) ≤ 1)

*EFbarn* Default NH3 emission factor for barn housing system (kg NH3-N kg-1 TAN) (**Table 43**)

**Eq. 4.3.1‑14**

where

*NH3\_Nbarn\_rate* Daily NH3-N emissions from beef barns (kg NH3-N head-1 day-1)

**Eq. 4.3.1‑15**

where

*NH3\_Nbarn* Daily NH3-N emissions from beef barns (kg NH3-N day-1), by animal group

*#cattle* Number of beef cattle

**Ammonia emissions from housing are calculated on a daily basis.**

### Manure NH3 volatilization from storage for beef cattle and dairy cattle (including calves)

This section calculates NH3 emissions from stored solid manure (stockpiled, composted) from different beef and dairy housing systems, and liquid manure (slurry pit, tank, lagoon) sourced from different dairy housing systems on a daily basis.

Ammonia N loss from stored solid beef manure and stored solid and liquid dairy manure is calculated from the amount of daily TAN that flows into the storage system and a default EF for each storage system(**Table 43**). The daily TAN mass flows from the different housing systems to storage are calculated by subtracting daily NH3-N volatilization losses from the daily excreted TAN in the housing stage. The calculation of NH3-N losses from stored manure uses the available TAN left after housing losses and TAN sourced from mineralization of organic N from faecal and bedding N. If manure is removed from storage and applied to fields on the simulated farm, added to an AD system or exported from the farm, then the corresponding amount of TAN is subtracted from the storage system and reflected in the amount of TAN remaining in storage on the following day.

During manure storage, mineralization, nitrification and immobilization take place, which influence the amount of TAN in stored manure, impacting NH3 production. Immobilization and mineralization rates of N compounds are influenced by the C:N ratio of the organic matter in manure. If the C:N ratio is lower than 25:1, the N supply exceeds microbial demand resulting in net mineralization. When the C:N ratio is higher than 25:1, the N supply is lower than the microbial demand so that N is immobilized (Sims and Stehouwer, 2008). However, immobilization of TAN is estimated to be zero (*fimmobilized = 0*) for all manure types, and the fractions of organic N mineralized (*fmineralized)* as TAN during manure storage were estimated as 0.46 for composted manure (*over a 10 month period*) and 0.28 for stockpiled/deep bedding manure (*over a 4 month period*) for western Canada (Chai et al., 2014), and 0.10 for liquid dairy manure with or without a natural crust (Chai et al., 2016). The nitrification and denitrification of N compounds in stored manure are affected by the oxygen content, and as such, composted manure has a higher fraction of nitrified TAN than stockpiled/deep bedding manure because of its higher oxygen content. Values for the fraction of TAN nitrification (*fnitrified*), fraction of TAN denitrification (*fdenitrified*), and emissions of N2O-N, NO-N and N2-N vary depending on the livestock and manure type and are provided in **Table 44**. For dairy animals, EFs of N2O, NO and N2 and the fraction of leached/runoff N from manure are primarily generated from nitrifying TAN and denitrifying nitrate, and thus are correlated to the initial TAN concentration of the stored manure.

The default NH3 *EFstorage* (**Table 43**) is adjusted to account for temperature changes to create *EFstorage\_adju*, calculated separately for beef solid, dairy solid and dairy liquid manure.

#### Manure TAN in storage and N loss as manure ammonia for beef cattle and dairy cattle (including calves)

**Eq. 4.3.2‑1**

where

*TANflowstorage* Amount of TAN entering the storage system each day (minus housing NH3-N emissions) (kg TAN day-1), by animal group and management system

*TANexcretion* TAN excreted on the current day (kg TAN day-1), by animal group and manure management system

*NH3\_Nhousing* Daily NH3-N emissions from the housing system on the current day (kg NH3-N day-1), by animal group and manure management system

**Eq. 4.3.2‑2**

where

*TANflowstorage(1)* Amount of TAN entering the storage system each day (minus housing NH3-N emissions) from beef cattle and dairy cattle manure (kg TAN day-1), adjusted for nitrification and denitrification of N compounds, by animal group and manure management system

*fimmobilized* Fraction of TAN that is immobilized to organic N during manure storage, dimensionless (**Table 44**)

*fnitrified* Fraction of TAN that is nitrified during manure storage, dimensionless (**Table 44**)

*FaecalNexcretion* Daily N excreted through faeces (kg N day-1), by animal group and manure management system

*Nbedding* Daily bedding N (kg N day-1), by animal group and manure management system

*fmineralized* Fraction of organic N that is mineralized as TAN during manure storage, dimensionless (**Table 44**)

**For solid manure storage for beef cattle (including calves):**

**Eq. 4.3.2‑3**

where

*ATAsolidstorage\_beef* Ambient temperature-based adjustments used to correct default NH3 emission factors for solid beef manure storage (deep bedding, solid storage/stockpiled, compost)

*T* Average daily temperature (°C)

**For solid manure storage for dairy cattle (including calves):**

**Eq. 4.3.2‑4**

where

*ATAsolidsotrage\_dairy* Ambient temperature-based adjustments used to correct default NH3 EFs for solid dairy manure storage (deep bedding, solid storage/stockpiled, compost). The effect of temperature in storage was assumed to be a Q10 of 1.7 (1.7-fold change in rate per 10 °C change in temperature), solid manure was assumed to generate heat in storage raising its temperature 2 °C above ambient air temperature

*T* Average daily temperature (°C)

**For liquid manure storage for dairy cattle (including calves):**

**Eq. 4.3.2‑5**

where

*ATAliquidstorage\_dairy* Ambient temperature-based adjustments used to correct default NH3 EFs for liquid dairy manure storage (tank, slurry pit, lagoon/earthen storage)

*T* Average daily temperature (°C)

**Eq. 4.3.2‑6**

where

*EFstorage\_adju* Adjusted NH3 emission factor (kg NH3-N kg-1 TAN ) for stored manure **(0 ≤ *EFstorage\_adju* ≤ 1)**

*EFstorage* Default NH3 emission factor by manure storage system (kg NH3-N kg-1 TAN) (**Table 43**)

**Eq. 4.3.2‑7**

where

*NH3-Nstorage* Daily NH3-N emissions from stored beef cattle and dairy cattle manure (kg NH3-N), by animal group and manure management system

**Eq. 4.3.2‑8**

where

TANflowstorage\_adju Amount of TAN entering the storage system each day (minus housing and storage NH3-N emissions) from beef cattle and dairy cattle manure (kg TAN day-1), by animal group and manure management system

**Eq. 4.3.2‑9**

where

*TANstorage(t)* TAN in storage on day *t* (kg TAN), by animal group and manure management system

*TANflowstorage(t-1)* TAN entering storage on day *t-1* (kg TAN), by animal group and manure management system

**Eq. 4.3.2‑10**

where

*Total\_TANstorage(t)* Amount of TAN in stored manure on day *t* (kg TAN), by livestock type and manure management system

**Ammonia emissions from storage are calculated on a daily basis as an iterative loop.**

#### Removal of manure from storage before the end of the year/simulation period

**Eq. 4.3.2‑11**

where

*Total\_TANstorage(t)* Amount of TAN in stored manure on day *t* (day following removal) (kg TAN), by livestock type and manure management system

*Total\_TANstorage(t-1)* Amount of TAN in stored manure on the day *t-1* (day of removal, prior to removal) (kg TAN), by livestock type and manure management system

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage on the day of removal (*t-1*, kg), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on the day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

### Manure NH3 volatilization from housing and storage for broilers, layers and turkeys

#### total ammonical nitrogen (TAN) for broilers, layers and turkeys

**Eq. 4.3.3‑1**

where

*TANexcretion* Total ammonical N (TAN) excretion (kg TAN day-1), by animal group - see box below

*#animals* Number of broilers, layers or turkeys

Holos V4 will use the following default values for *TANexcreted\_rate* and fraction of excreted uric acid/TAN emitted as NH3-N from housing and storage:

*TANexcretion\_ratebroilers1* 0.0007 kg TAN head-1 day-1

*TANexcretion\_ratelayers2* 0.0011 kg TAN head-1 day-1

*TANexcretion\_rateturkeys3* 0.0026 kg TAN head-1 day-1

*EFhousing\_broilers* 0.26 (for broiler housing on litter; from Sheppard et al., 2009b: “For manure management, broiler production was almost exclusively (99%) based on litter”)

*EFhousing\_layers* 0.25 (Sheppard et al. (2009b): This EF is for solid manure with no litter in layer housing; 12% of layer barns use litter; 57% based on solid manure and the remainder on slurry – for slurry, the EF would be 0.1)

*EFhousing\_turkeys* 0.20 (for housing on straw litter refreshed every 30 days or less; Sheppard et al. (2009b))

*EFstorage\_broilers* 0.087 (for storage of uncovered solid manure with or without litter at 15 °C, before temperature adjustment) (Sheppard et al., 2009b)

*EFstorage\_layers* 0.087 (for storage of uncovered solid manure with or without litter at 15 °C, before temperature adjustment) (Sheppard et al., 2009b)

*EFstorage\_turkeys* 0.087 (for storage of uncovered solid manure with or without litter at 15 °C, before temperature adjustment) (Sheppard et al., 2009b)

1 Daily TAN excretion values for broilers were calculated from the yearly value per bird place reported in Sheppard et al. (2009b) – 0.18 kg TAN bird place-1 year-1. This was adjusted to a daily per head value based on 273 production days per year in Canadian broiler systems (average of 42 days per production cycle \* 6.5 production cycles per year, Sheppard et al. 2009a): *TANexcretion* = 0.18 kg / 273 days = 0.00066 kg head-1 day-1

2 Daily TAN excretion values for layers were calculated from the yearly value per bird place reported in Sheppard et al. (2009b) – 0.40 kg TAN bird place-1 year-1. This was adjusted to a daily per head value based on 358 production days per year in Canadian layer systems (Sheppard et al. 2009a): *TANexcretion* = 0.40 kg / 358 days = 0.0011 kg head-1 day-1

3 Daily TAN excretion values for turkeys were calculated from the yearly value per bird place reported in Sheppard et al. (2009b) – 0.83 kg TAN bird place-1 year-1. This was adjusted to a daily per head value based on 320 production days per year in Canadian turkey systems (average of 107 days per production cycle \* 3 production cycles per year, Sheppard et al. 2009a): *TANexcretion* = 0.83 kg / 320 days = 0.0026 kg head-1 day-1

#### Faecal nitrogen for broilers, layers and turkeys

The amount of N excreted by broilers, layers and turkeys through faeces (faecal N) is calculated as the difference between total N excreted (*Nexcretion*) and the N excreted in urine/uric acid (*TANexcretion*).

**Eq. 4.3.3‑2**

where

*FaecalNexcretion\_rate* Faecal N excretion rate (kg N head-1 day-1), by animal group

**Eq. 4.3.3‑3**

where

*FaecalNexcretion* Total N excreted through faeces (kg N day-1), by animal group

*#animals* Number of broilers, layers or turkeys

#### Manure organic nitrogen (ON) for broilers, layers and turkeys

The total amount of organic N contained in manure is the sum of the faecal N excreted by the animal and the N contained in livestock bedding.

**Eq. 4.3.3‑4**

where

*OrganicNmanure* Daily organic N in excreted manure and bedding (kg N)

*Nbedding* N in bedding material (kg N)

#### Manure NH3 volatilization from housing for broilers, layers and turkeys

**Eq. 4.3.3‑5**

Derived from Sheppard et al. 2009b

where

*NH3\_Nhousing\_rate* Daily NH3-N loss from manure from housing for broilers, layers and turkeys (kg NH3-N head-1), by animal group and manure management system

*TANexcretion\_rate* Default value for daily TAN excretion for broilers, layers and turkeys derived from Sheppard et al. (2009a,b) – see box above

*EFhousing* Default emission factors for excreted uric acid or TAN emitted as NH3-N from housing for broilers, layers and turkeys from Sheppard et al. (2009a,b) – see box above

**Eq. 4.3.3‑6**

where

*NH3\_Nhousing* Daily NH3-N emissions from broiler, layer and turkey manure during the housing stage (kg NH3), by animal group and manure management system

*#animals* Number of broilers, layers or turkeys

**Ammonia emissions from housing are calculated on a daily basis.**

#### Manure NH3 volatilization from storage for broilers, layers and turkeys

Ammonia N loss from stored manure is calculated from the amount of TAN that flows into the storage system each day and a default EF for the storage system (see box above). The default EFs are adjusted to account for the effect of daily temperature changes.

**Eq. 4.3.3‑7**

where

*TANflowstorage* Adjusted amount of TAN entering the storage system each day (minus housing NH3-N emissions) (kg TAN day-1), by animal group and manure management system

*TANexcretion* TAN excretion (kg TAN day-1), by animal group and manure management system

*NH3-Nhousing* Daily NH3-N lost through NH3 emissions from the housing system (kg NH3-N day-1),by animal group and manure management system

**Eq. 4.3.3‑8**

Derived from Sheppard et al. 2009b

where

*ATAstorage* Ambient temperature-based adjustments used to correct default NH3 emission factors for the storage of solid poultry manure. The effect of temperature was assumed to be a Q10 of 1.7 (1.7-fold change in rate per 10 °C change in temperature), solid manure was assumed to generate heat in storage raising its temperature 2 °C above ambient air temperature (Sheppard et al., 2009b)

*T* Daily average outdoor temperature (°C)

**Eq. 4.3.3‑9**

Derived from Sheppard et al. 2009b

where

*EFstorage\_adju* Temperature-adjusted daily NH3-N loss from manure in storage for broilers, layers and turkeys (kg NH3-N) **(0 ≤ *EFstorageadju* ≤ 1)**

*EFstorage* Default fractions of excreted uric acid or TAN emitted as NH3-N from manure in storage for broilers, layers and turkeys from Sheppard et al. (2009b) – see box above

**Eq. 4.3.3‑10**

Derived from Sheppard et al. 2009b

where

*NH3\_Nstorage* Daily NH3-N emissions from manure in storage for broilers, layers and turkeys (kg NH3-N), by animal group and manure management system

**Eq. 4.3.3‑11**

where

*TANflowstorage\_adju* Amount of TAN entering the storage system each day (minus housing and storage NH3-N emissions) in broiler, layer and turkey manure (kg TAN day-1), by animal group and manure management system

**Eq. 4.3.3‑12**

where

*TANstorage(t)* TAN in storage on day *t* (kg TAN), by animal group and manure management system

*TANstorage(t-1)* TAN in storage on day *t-1* (kg TAN), by animal group and manure management system

*TANflowstorage\_adju(t)* Amount of TAN entering the storage system on day *t* in broiler, layer and turkey manure (kg TAN day-1), by animal group and manure management system

**Eq. 4.3.3‑13**

where

*Total\_TANstorage(t)* Amount of TAN in stored manure on day *t* (kg TAN), by livestock type and manure management system

**Ammonia emissions from storage are calculated on a daily basis.**

#### Removal of manure from storage before the end of the year/simulation period

**Eq. 4.3.3‑14**

where

*Total\_TANstorage(t)* Amount of TAN in stored manure on day *t* (day following removal) (kg TAN), by livestock type and manure management system

*Total\_TANstorage(t-1)* Amount of TAN in stored manure on day *t-1* (day of removal, prior to removal) (kg TAN), by livestock type and manure management system

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage on day of removal (*t-1*, kg), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

### Manure NH3 volatilization from housing and storage for sheep, swine and other livestock

#### Urinary Nitrogen/Total ammoniacal nitrogen (TAN) for sheep (including lambs)

**Eq. 4.3.4‑1**

where

*TANexcretion\_rate* TAN excretion rate (kg TAN head-1 day-1)

*FracurinaryN* Fraction of N excreted in urine (urinary-N or urea-N fraction), which varies with dietary CP content (kg N kg-1 total N excreted). For sheep, the *FracurinaryN* values for beef cattle are used (see box in **section 4.3.1.1**)

**Eq. 4.3.4‑2**

where

*TANexcretion* TAN excretion (kg TAN day-1), by animal group

*#sheep* Number of sheep

#### Faecal Nitrogen for sheep (incliuding Lambs)

The amount of N excreted by sheep through faeces (faecal N) is calculated as the difference between total N excreted (*Nexcretion*) and N excreted in urine (*TANexcretion*)

**Eq. 4.3.4‑3**

where

*FaecalNexcretion\_rate* Faecal N excretion rate (kg N head-1 day-1)

**Eq. 4.3.4‑4**

where

*FaecalNexcretion* Total N excreted through faeces (kg N day-1), by animal group

*#sheep* Number of sheep

#### Manure Organic nitrogen (ON) for sheep (including lambs)

The total amount of organic N contained in manure is the sum of the faecal N excreted by the animal and the N contained in the livestock bedding.

**Eq. 4.3.4‑5**

where

*OrganicNmanure* Daily organic N in excreted manure and bedding (kg N), by animal group

*Nbedding* N in bedding material (kg N) – this is zero for lambs as the N in the bedding is already accounted for in the *Nbedding* for ewes

#### Manure NH3 volatilization from housing and storage for sheep, swine and other livestock

**Eq. 4.3.4‑6**

Derived from IPCC 2019, Eq. 10.26

where

*NH3\_Nhousing,storage\_rate* Manure N losses via NH3 volatilization during housing and storage for sheep, swine, and other livestock manure systems (kg NH3-N), by animal group and manure management system

*Fracvolatilization* Volatilization fraction for sheep, swine and other livestock types (**Table 36**)

**Eq. 4.3.4‑7**

*where*

*NH3-Nhousing,storage* Total manure N losses via NH3 volatilization during housing and storage for sheep, swine, and other livestock manure systems (kg N), by animal group and manure management system

*#animals* Number of animals

**Ammonia emissions from housing and storage are calculated on a daily basis.**

### N2O volatilization from manure in housing and storage for all livestock

In the previous version (Holos V3), the fraction of N lost through volatilization was calculated based on default IPCC (2006) volatilization loss fractions (*Fracvolatilization*) for each livestock type. However, in the current version, *Fracvolatilization* values for beef and dairy cattle and poultry are calculated based on *Nexcretion*, *Nbedding* and NH3-N losses during housing and storage, using **Eq. 4.3.5‑1**. For swine, sheep and other livestock, *Fracvolatilization* values from IPCC (2019) (**Table 36**) are used.

**Note:** For beef cattle, dairy cattle and broilers, layers and turkeys, the user also has the option to use IPCC (2019) *Fracvolatilization* values as follows: Beef cattle: solid storage – 0.45; compost (intensive windrow) – 0.65; compost (passive windrow) – 0.60; deep bedding (> 1 month, no mixing) – 0.25; Dairy cattle: daily spread – 0.07; solid storage – 0.30; compost (intensive windrow) – 0.50; compost (passive windrow) – 0.45; deep bedding (> 1 month, no mixing) – 0.25; liquid/slurry with natural crust cover – 0.3; liquid/slurry, without natural crust cover – 0.48; liquid slurry, cover – 0.10; deep pit under barn – 0.28; Poultry: manure with litter – 0.4; manure without litter – 0.48.

**For beef and dairy cattle (including beef and dairy calves) and broilers, layers and turkeys:**

**Eq. 4.3.5‑1**

where

*Fracvolatlization* Fraction of manure N volatilized as NH3 and NOx by animal group and manure management system

*NH3\_Nhousing* Daily NH3-N emissions during housing of beef cattle, dairy cattle and broilers, layers and turkeys (kg NH3-N day-1), by animal group

*NH3\_Nstorage* DailyNH3-N emissions during storage of manure from beef cattle, dairy cattle and broilers, layers and turkeys (kg NH3-N day-1), by animal group

*Nexcretion* Total amount of N excreted by beef or dairy cattle, broilers, layers or turkeys (kg N day-1), by animal group

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group

**For all livestock:**

**Eq. 4.3.5‑2**

Derived from IPCC 2019, Eq. 10.26, Eq. 10.28

*where*

*N2O-Nvolatilization\_rate* Indirect N2O emissions from manure volatilization (kg head-1 day-1), by animal group and manure management system

*Fracvolatilization* NH3volatilization fraction - estimated for beef cattle and dairy cattle and broilers, layers and turkeys; default values for sheep, swine, and other livestock types (**Table 36**)

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**, by manure management system)

**Eq. 4.3.5‑3**

*where*

*N2O-Nvolatilization* Indirect N2O emissions frommanure volatilization (kg N2O-N), by animal group

*#animals* Number of animals

**Indirect N2O emissions are calculated on a daily basis for all animal groups.**

#### Adjustment of NH3 volatilization estimates from housing and storage following indirect N2O emissions

As indirect N2O emissions to the atmosphere from livestock manure derive from NH3 volatilized from manure during the housing and storage stages, for the livestock types for which we estimate NH3 emissions (i.e., beef and dairy cattle, broilers, layers and turkeys), the estimates of NH3 emissions during these stages need to be adjusted to avoid double-counting. This is achieved by subtracting the indirect N2O-N losses resulting from NH3 volatilization to give a final estimate of net NH3 losses from these sources. These adjustments need to be carried out for each animal group and for each housing and manure storage system.

**For NH3 emissions from beef and dairy cattle, and broiler, layer and turkey manure during the housing stage:**

**Eq. 4.3.5‑4**

where

*Fracvolatilization\_housing* Fraction of manure N volatilized as NH3 and NOx during the housing stage

*NH3\_Nhousing* Daily NH3-N emissions during the housing stage from beef cattle, dairy cattle, and broilers, layers and turkeys (kg NH3-N day-1), by animal group and manure management system

*Nexcretion* N excreted by beef or dairy cattle or broilers, layers or turkeys (kg N day-1), by animal group

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group

**Eq. 4.3.5‑5**

where

*N2O-Nvolatilization\_housing* Indirect N2O emissions during the housing stage (kg N2O-N day-1), by animal group and manure management system

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**, by handling system)

**Eq. 4.3.5‑6**

where

*NH3\_Nhousing\_adju* Adjusted daily NH3-N emissions from beef and dairy cattle, and broiler, layer and turkey manure during the housing stage (kg NH3-N day-1), by animal group and manure management system

**For NH3 emissions from beef and dairy cattle, and broiler, layer and turkey manure during the manure storage stage:**

**Eq. 4.3.5‑7**

where

*Fracvolatilization\_storage* Fraction of manure N volatilized as NH3 and NOx during the manure storage stage

*NH3\_Nstorage* Daily NH3-N emissions during the storage of manure from beef cattle, dairy cattle, and broilers, layers and turkeys (kg NH3-N day-1), by animal group and manure management system

*Nexcretion* Total amount of N excreted by beef cattle, dairy cattle, and broilers, layers and turkeys (kg N day-1), by animal group

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group

**Eq. 4.3.5‑8**

where

*N2O-Nvolatilization\_storage* Manure volatilization N emissions during the manure storage stage (kg N2O-N day-1), by animal group and manure management system

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**, by handling system)

**Eq. 4.3.5‑9**

where

*NH3\_Nstorage\_adju* Adjusted daily NH3-N emissions from beef and dairy cattle, and broiler, layer and turkey manure during the storage stage (kg NH3-N day-1), by animal group and manure management system

**Adjusted ammonia emissions from housing and storage are calculated on a daily basis.**

**For NH3 emissions from housing + storage for all other livestock types:**

For all other livestock types, combined housing and storage values for NH3-N and indirect N2O-N emissions from manure are estimated.

**Eq. 4.3.5‑10**

where

*NH3\_Nstorage\_adju* Adjusted daily NH3-N emissions from sheep, swine and other livestock types during the housing and storage stages (kg NH3-N day-1), by animal group and manure management system

*NH3\_Nhousing,storage* Total manure N losses via NH3 volatilization from manure during the housing and storage stages for sheep, swine, and other livestock types (kg NH3-N day-1), by animal group and manure management system

*N2O-Nvolatilization* Manure volatilization N emissions during the housing and manure storage stages (kg N2O-N day-1), by animal group and manure management system

### Indirect N2O losses from manure via leaching and runoff

**Eq. 4.3.6‑1**

Derived from IPCC 2019, Eq. 10.27, Eq. 10.29

where

*N2O-Nleaching\_rate* N2O-N losses from manure leaching (kg N2O-N head-1 day-1), by animal group and manure management system

*Fracleach* Leaching fraction (**Table 36**, by livestock type and manure handling system)

*EFleach* Emission factor for leaching [kg N2O-N (kg N)-1] (**Table 36**, by manure handling system)

**Eq. 4.3.6‑2**

where

*N2O-Nleaching* Manure leaching N emissions (kg N2O-N day-1), by animal group

*#animals* Number of animals

**Eq. 4.3.6‑3**

where

*NO3\_Nleaching* NO3-N leached from manure during storage (kg NO3-N), by animal group

### Total indirect N2O emissions from manure

**For all animal groups (including beef and dairy calves and other livestock young):**

**Eq. 4.3.7‑1**

where

*N2O-Nindirectmanure* Total indirect N2O-N emissions from livestock manure (kg N2O-N), by animal group

### Total N2O emissions from manure

**For all animal groups:**

**Eq. 4.3.8‑1**

where

*N2O-Nmanure* Total direct and indirect manure N2O emissions (kg N2O), by animal group

## Total emissions

Emissions from manure during housing and storage should be summed for all animal groups within each livestock type (i.e., beef cattle, dairy cattle, swine, poultry, etc.).

### Manure CH4 emissions

**Eq. 4.4.1‑1**

where

*Total\_CH4manure* Total manure CH4 emissions (kg CH4 year-1), by livestock type

*CH4manure* Manure CH4 emissions (kg CH4), by animal group

### Manure N emissions

**Eq. 4.4.2‑1**

where

*Total\_N2O-Ndirectmanure* Total direct N2O emissions (kg N2O-N year-1), by livestock type

*N2O-Ndirectmanure* Direct N2O emissions (kg N2O-N), by animal group

**Eq. 4.4.2‑2**

where

*Total\_NH3\_Nhousing* Total NH3 emissions from housing (kg NH3 year-1), by livestock type

*NH3housing* Manure NH3 emissions from housing systems (kg NH3), by animal group

**Eq. 4.4.2‑3**

where

*Total\_NH3\_Nstorage* Total NH3 emissions from manure storage systems (kg NH3-Nyear-1), by livestock type

*NH3storage* Manure NH3 emissions from manure storage systems (kg NH3-N), by animal group

**Eq. 4.4.2‑4**

where

*Total\_NH3\_N*Total NH3 emissions from manure during housing and storage (kg NH3-N year-1), by livestock type

**Eq. 4.4.2‑5**

where

*Total\_N2O-Nvolatilization* Total N2O emissions from manure (kg N2O-N year-1), by livestock type

*N2O-Nvolatilization* N2O emissions from manure (kg N2O-N), by animal group

**Eq. 4.4.2‑6**

where

*Total\_N2O-Nleaching* Total manure leaching N emissions (kg N2O-N year-1), by livestock type

*N2O-Nleaching* Manure leaching N emissions (kg N2O-N), by animal group

**Eq. 4.4.2‑7**

where

*Total\_NO3-Nleaching* Total manure leaching NO3-N emissions (kg NO3-N year-1), by livestock type

*NO3-Nleaching* Manure leaching NO3-N emissions (kg NO3-N year-1), by animal group

**Eq. 4.4.2‑8**

where

*Total\_N2O-Nindirectmanure* Total indirect N emissions from manure (kg N2O-N year-1), by livestock type

**Eq. 4.4.2‑9**

where

*Total\_N2O-Nmanure* Total manure N emissions (kg N2O-N year-1), by livestock type

## Manure available for land application, addition to an anaerobic digestion system or export

(by A.W. Alemu, S.J. Pogue and P. Mantle)

### Total carbon available for all livestock types

On a given day, the total amount of C available in stored manure for a specific livestock type, and thus for application to land, addition to an AD system or export from the simulated farm, is equal to the sum of available manure C in storage for all animal groups within a specific livestock type calculated for each manure management system using **Eq. 4.1.3‑16** for farm-produced manure. This value reflects any previous manure removals from storage (see **Eq. 4.1.3‑17**). The total amount of C available also includes the C in anaerobic digestate produced on-farm, as well as the C in imported manure, which is calculated as the product of the amount of manure imported and the C content of the manure, which depends on the livestock type and the manure management system.

### Total nitrogen available for all livestock types

#### nitrogen available from beef and dairy cattle manure

The total amount of N in farm-produced beef and dairy cattle manure available for application to land, addition to an AD system or export in beef and dairy cattle manure is the sum of inorganic TAN and organic (faecal + bedding) N in stored manure minus storage N losses (e.g., TAN lost via NH3 emissions and organic N lost via leaching and runoff as manure flows from the housing stage into the manure storage stage).

##### Total ammonical nitrogen (TAN)

**Eq. 4.5.2‑1**

where

*TANlandmanure(t)* TAN available in stored beef or dairy cattle manure on day *t* (kg TAN), by animal group and manure management system

*TANstorage(t)* TAN in stored manure on day *t* (kg TAN), by animal group and manure management system, calculated using **Eq. 4.3.2‑9**

**Eq. 4.5.2‑2**

where

*Total\_TANlandmanure(t)* Total TAN available in stored beef or dairy cattle manure on day *t* (kg TAN), by livestock type and manure management system

##### Organic nitrogen (ON)

Total organic N available for land application, addition to an AD system or export considers faecal N and bedding N as an input and the losses due to mineralization during NH3 emissions and N loss as direct N2O and via leaching during the housing and storage stages.

**Eq. 4.5.2‑3**

where

*OrganicNflowlandmanure* Amount of organic N entering the pool of available manure organic N in storage each day (kg N day-1), by animal group and manure management system

*Nexcretion* Amount of total N excreted (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑29**

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑31**

*fmineralized* Fraction of organic N that is mineralized as TAN during beef or dairy cattle manure storage, dimensionless (**Table 44**)

*N2O-Ndirectmanure* Manure N loss as direct N2O-N during manure storage (kg N2O-N day-1), by animal group, calculated using **Eq. 4.2.2‑2**

*N2O-Nleaching* Manure N2O-N loss as leaching during manure storage (kg N2O-N day-1), by animal group, calculated using **Eq. 4.3.6‑2**

*NO3\_Nleaching* Manure NO3-N loss as leaching during manure storage (kg NO3-N day-1), by animal group, calculated using **Eq. 4.3.6‑3**

**Eq. 4.5.2‑4**

where

*OrganicNlandmanure(t)* Organic N available in stored beef or dairy cattle manure on day *t* (kg N), by animal group and manure management system

*OrganicNlandmanure(t-1)* Organic N available in stored beef or dairy cattle manure on day *t-1* (kg N), by animal group and manure management system

**Eq. 4.5.2‑5**

where

*Total\_OrganicNlandmanure(t)* Total organic N available in stored beef or dairy cattle manure on day *t* (kg N), by livestock type and manure management system

##### Total manure nitrogen

**Eq. 4.5.2‑6**

where

*Nlandmanure(t)* Total N available in stored beef or dairy cattle manure on day *t* (kg N), by animal group and manure management system

**Eq. 4.5.2‑7**

where

*Total\_Nlandmanure* Total N available in stored beef or dairy cattle manure on day *t* (kg N), by livestock type and manure management system

##### Removal of manure from storage before the end of the year/simulation period

**Eq. 4.5.2‑8**

where

*Total\_TANlandmanure(t)* Total amount of TAN available in manure remaining in storage on day *t* (day following removal) (kg TAN), by livestock type and manure management system

*Total\_TANstorage(t)* TAN in stored manure on day *t* (day following removal) (kg TAN), by livestock type and manure management system, calculated using **Eq. 4.3.2‑11**

**Eq. 4.5.2‑9**

where

*Total\_OrganicNlandmanure(t)* Total amount of organic N in manure available on day *t* (day following removal) (kg N), by livestock type and manure management system

*Total\_OrganicNlandmanure(t-1)* Total amount of organic N in manure available on day *t-1* (day of removal, prior to removal) (kg N), by livestock type and manure management system

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage (kg) on the day of remova (*t-1*), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on the day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

**Eq. 4.5.2‑10**

where

*Total\_Nlandmanure(t)* Total amount of N available in stored manure on day *t* (day following removal) (kg N), by livestock type and manure management system

#### nitrogen available from broiler, layer and turkey manure

##### Total ammonical nitrogen (TAN)

**Eq. 4.5.2‑11**

where

*TANlandmanure(t)* Total amount of TAN available in stored broiler, layer or turkey manure on day *t* (kg TAN), by animal group and manure management system

*TANstorage(t)* TAN in stored manure on day *t* (kg TAN), by animal group and manure management system

**Eq. 4.5.2‑12**

where

*Total\_TANlandmanure* Total TAN available in stored broiler, layer or turkey manure (kg TAN), by livestock type and manure management system

##### Organic nitrogen (ON)

For broilers, layers and turkeys, the amount of organic N in manure available for application to land, addition to an AD system- or export is calculated as the difference between *Nlandmanure* and *TANlandmanure*.

**Eq. 4.5.2‑13**

where

*OrganicNlandmanure* Organic N available in stored broiler, layer or turkey manure (kg N), by animal group and manure management system

*Nlandmanure* N available in stored broiler, layer or turkey manure (kg N), by animal group and manure management system, calculated using **Eq. 4.5.2‑16**

**Eq. 4.5.2‑14**

where

*Total\_OrganicNlandmanure* Total organic N in stored broiler, layer or turkey manure (kg TAN day-1), by livestock type and manure management system

##### Total manure nitrogen

**Eq. 4.5.2‑15**

where

*Nflowlandmanure* Amount of N entering the pool of manure N available in storage (kg N day-1), by animal group and manure management system

*Nexcretion* Amount of total N excreted (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑29**

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑31**

*N2O-Ndirectmanure* Manure N loss as direct N2O-N (kg N day-1), by animal group, calculated in **Eq. 4.2.2‑2**

*NH3\_Nhousing* Manure N loss as NH3-N (kg NH3-N day-1) during housing, by animal group, calculated using **Eq. 4.3.3‑6**

*NH3\_Nstorage* Manure N loss as NH3-N (kg NH3-N day-1), by animal group, calculated using **Eq. 4.3.3‑10**

*N2O-Nleaching* Manure N loss via leaching (kg N2O-N day-1), by animal group, calculated using **Eq. 4.3.6‑2**

*NO3\_Nleaching* Manure NO3-N loss as leaching during manure storage (kg NO3-N day-1), by animal group, calculated using **Eq. 4.3.6‑3**

**Eq. 4.5.2‑16**

where

*Nlandmanure(t)* N in manure available in storage on day *t* (kg N), by animal group and manure management system

*Nlandmanure(t-1)* N in manure available in storage on day *t-1* (kg N), by animal group and management system

**Eq. 4.5.2‑17**

where

*Total\_Nlandmanure* Total N in manure available in storage on day *t* (kg N), by livestock type and manure management system

##### Removal of manure from storage before the end of the year/simulation period

**Eq. 4.5.2‑18**

where

*Total\_TANlandmanure(t)* Total amount of TAN in manure available in storage on day *t* (day following removal) (kg TAN), by livestock type and manure management system

*Total\_TANstorage(t)* TAN in stored manure on day *t* (day following manure removal), by livestock type and management system (kg TAN), calculated using **Eq. 4.3.3‑14**

**Eq. 4.5.2‑19**

where

*Total\_OrganicNlandmanure(t)* Total amount of organic N available in stored manure on day *t* (day following removal) (kg N), by livestock type and manure management system

**Eq. 4.5.2‑20**

where

*Total\_Nlandmanure(t)* Total amount of N available in stored manure on day *t* (day following removal) (kg N), by livestock type and manure management system

*Total\_Nlandmanure(t-1)* Total amount of N available in stored manure on day *t-1* (day of removal, prior to removal) (kg N), by livestock type and manure management system

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage on the day of removal day *t-1* (kg), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on the day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated **Eq. 4.5.3‑3**

#### nitrogen available from sheep, swine and other livestock manure

##### Total nitrogen available from farm-produced sheep, swine and other livestock manure

**Eq. 4.5.2‑21**

where

*Nflowlandmanure* Amount of N entering the pool of available N in stored manure each day (kg N day-1), by animal group and manure management system

*Nexcretion* Amount of total N excreted (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑29**

*Nbedding* Total amount of N added from bedding materials (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑31**

*N2O-Ndirectmanure* Manure N loss as direct N2O (kg N2O-N day-1), by animal group, calculated using **Eq. 4.2.2‑2**

*NH3\_Nihousing,storage* Manure N loss as NH3 (kg NH3-N day-1) (volatilization), by animal group, calculated using **Eq. 4.3.4‑7**

*N2O-Nleaching* Manure N loss via leaching (kg N2O-N day-1), by animal group, calculated using **Eq. 4.3.6‑2**

*NO3\_Nleaching* Manure NO3-N loss as leaching during manure storage (kg NO3-N day-1), by animal group, calculated using **Eq. 4.3.6‑3**

**Eq. 4.5.2‑22**

where

*Nlandmanure(t)* Total N available in stored manure on day *t* (kg N), by animal group and manure management system

*Nlandmanure(t-1)* Total N available in stored manure on day *t-1* (kg N), by animal group and manure management system

**Eq. 4.5.2‑23**

where

*Total\_Nlandmanure* Total N available in stored manure on day *t* (kg N), by livestock type and manure management system

##### Removal of farm-produced manure from storage before the end of the year/simulation period

**Eq. 4.5.2‑24**

where

*Total\_Nlandmanure(t)* Total amount of N available in stored manure on day *t* (day following removal) (kg N), by livestock type and manure management system

*Total\_Nlandmanure(t-1)* Total amount of N available in stored manure on day *t-1* (day of removal, prior to removal) (kg N), by livestock type and manure management system (kg N)

*Volumemanureremoved(t-1)* Volume of each type of manure removed from storage on the day of removal day *t-1* (kg), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

*Total\_Volumelandmanure(t-1)* Amount of each type of manure available on the day of removal (*t-1*, prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

### Weight/volume of farm-produced stored manure available for application to land, addition to an AD system or export

The amount of manure produced on-farm is calculated based on the amount of manure N remaining in storage and default manure N concentration values for different animal groups and manure types/manure management systems (**Table 6**). This accounts for any removals of farm-produced manure from storage throughout the simulation period. Ammonia emissions from the land application of manure are estimated in **sections 4.6.2.1** (beef and dairy cattle), **4.6.2.2** (broilers, layers and turkeys) and **4.6.2.3** (sheep, swine and other livestock). These estimates are then input to the equations to estimate indirect N2O emissions following manure application. Carbon dioxide emissions relating to manure application are estimated in the land management section.

#### Manure carbon to nitrogen ratio

**Eq. 4.5.3‑1**

where

*ManureCNratio* C to N ratio of farm-produced stored manure and imported manure (fraction), by animal group and manure type/management system

#### Total manure produced (wet weight)

**Eq. 4.5.3‑2**

where

*Volumelandmanure* Volume of manure available in storageby animal group and manure management system on a given day (1000 kg wet weight for solid manure and 1000 litres for liquid manure – we assume that 1 kg of liquid manure = 1 L of liquid manure)

*Nlandmanure* Total N available in stored manure (kg N), by animal group and manure management system

*Ncontent* N content of solid and liquid manure (default values for different animal groups and manure management systems; % wet weight) (**Table 6**)

**Eq. 4.5.3‑3**

where

*Total\_Volumelandmanure* Total volume of manure available in storage (1000 kg wet weight for solid manure and 1000 litres for liquid manure – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system. If imported manure is applied on-farm, this calculation is also applied to that manure for the specified livestock type and manure management system

***Total\_Volumelandmanure* is inserted into the Energy CO2 equation (Eq. 6.3.1‑2) to estimate the amount of energy used for manure application.**

**For estimation of the volume, N and C content of fresh and stored digestate available for application to agricultural land, see section 4.8.6**

## Emissions from land application of stored manure

(by S.J. Pogue, A.W. Alemu and P. Mantle)

### Direct N2O emissions from land-applied farm-produced and imported manure

Direct N2O emissions from land-applied manure are estimated for each field based on the specified manure application rate for the field. All manure N remaining after the specified application to the farm’s fields is automatically applied and the associated emissions estimated, with this remaining manure N spread equally among the farm’s fields (excl. native rangeland, if present). The equations below for the estimation of direct N2O emissions from land-applied manure apply both to farm-produced manure and imported manure spread on the simulated farm’s fields.

**Note:** all direct and indirect N2O emissions from land-applied manure reported in the Holos outputs relate to the sum of emissions from user-specified manure application (including imported manure) and ‘leftover’ manure for each year of the simulation. In the event that there is manure in storage (produced by animals in confined housing systems) in a given year and the model user does not specify a manure application, Holos will apply this manure evenly across the farm’s fields (excl. native rangeland), and report the associated emissions. In such scenarios, Holos assumes a default application date of 01 Oct (based on the 2011 Farm Environmental Management Survey (AAFC, 2016), which reported that “Across Canada, most land received solid manure application in fall (43%) or spring (25%). For liquid manure season of application was fairly evenly split between spring (25%), fall (22%), and “spring & fall” (23%).) For liquid manure application in such scenarios, Holos also assumes slurry broadcasting is the default application method for liquid manure.

**To calculate N2O from manure application on a specific field in the land management component:**

**Eq. 4.6.1‑1**

where

*N2O-Nmanuredirect(t,field n)* Direct N2O emissions (kg N2O-N) from manure application on field *n* in year *t*

*Total\_Nmanuretype(t,field n)* Total N inputs from all land-applied (farm-produced and imported) manure (kg N), specific to the manure type and the field (*n*) to which it was applied, in year *t*

*EFi,ON,l,m,n* Emission factor for organic (manure) N specific to field *n* (kg N2O -N kg-1 N), calculated using **Eq. 2.5.4‑1**

**Eq. 4.6.1‑2**

where

*Nmanure(t field n)* Total amount of farm-produced and imported manure N (kg) applied to field *n* in year *t*

***Any manure not applied to a specific field (‘leftover’ manure) is considered a further source of direct N2O emissions. For this* purpose*, it is assumed that the ‘leftover’ manure is spread equally across the farm’s fields (excl. native rangeland, if present),* meaning that the emission factor is averaged across all available fields (excl. native rangeland), weighted by their area.**

**Eq. 4.6.1‑3**

where

Emission factor for leftover organic (manure) N applied across the farm’s fields, calculated as an average across all available fields (excl. native rangeland, if present), weighted by their area (kg N2O-N kg-1 N)

**Eq. 4.6.1‑4**

where

*Nlandmanureremaining(t)* Stored manure N available for application to land minus stored manure N applied to specific fields or exported (kg N) in year *t*

**Note:** this includes all N in leftover digestate that is not applied to specific fields in year *t* (kg N)

*Total\_Nlandmanure(t)* Total N available in farm-produced stored manure (kg N) in year *t*, by livestock type and manure management system

**Note:** this includes all N available in digestate (*Nlanddigestate\_\_\_\_\_(t)*, kg N) in year *t*, by digestate type

*Nmanure,allfields(t)* Total amount of farm-produced and imported manure N (kg) applied to specific fields in year *t*

**Note:** this includes the total amount of N added to specific fields in all land-applied digestate (*Ndigestate\_\_\_\_\_allfields(t)*, kg N) in year *t*

*Nimported(t)* Total N imported to the farm and applied to land in year *t* (kg N)

*Total\_Nmanure\_export(t)* Total N (kg N) exported from the farm as manure in year *t*

**Eq. 4.6.1‑5**

where

*N2O-Nmanuredirect\_leftover(t)* Direct N2O emissions (kg N2O-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) in year *t*

**Eq. 4.6.1‑6**

where

*N2O-Nmanuredirect\_leftover(t,field n)* Direct N2O emissions (kg N2O-N) from the application of ‘leftover’ stored manure to field *n* in year *t*

**Note:** for year *t*, all manure produced by on-farm livestock is automatically applied to the farm's fields, even if the user does not specify any manure additions in the model interface. Thus, the total amount of manure N applied is equal to the total amount of manure N in storage available for application to land

**Eq. 4.6.1‑7**

where

*Nmanuretype\_export(t)* Total amount of N exported from the farm in farm-produced manure (kg N) in year *t*, specific to the manure type

*Total\_Nlandmanure(t)* Total N in farm-produced stored manure available for land application, addition to an AD system or export (kg N) in year *t*, by livestock type and manure management system

*Volumemanureremoved(t)* Volume of each type of manure removed from storage for export (kg) in year *t*, specific to the manure type

*Total\_Volumelandmanure(t)* Amount of each type of manure available in year *t* (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

**Eq. 4.6.1‑8**

where

*Total\_Nmanure\_export(t)* Total N (kg N) exported from the farm in manure in year *t*

**Eq. 4.6.1‑9**

where

*N2O-Nmanuredirect\_export(t,farm)* Direct N2O emissions (kg N2O-N) calculated for manure exported from the farm (as if applied) in year *t*

**To estimate total direct N2O-N losses from a specific field following manure application:**

**Eq. 4.6.1‑10**

where

*N2O-Nallmanuredirect(t,field n)* Total direct N2O emissions (kg N2O-N) from the application of all stored and imported manure on field *n* in year *t*

*N2O-Nmanuredirect(t,field n)* Direct N2O emissions (kg N2O-N) from manure application on field *n* in year *t*

*N2O-Nmanuredirect\_leftover(t,field n)* Direct N2O emissions (kg N2O-N) from the application of ‘leftover’ stored manure to field *n* in year *t*

**To estimate total N2O-N losses from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.1‑11**

where

*N2O-Nallmanuredirect(t,farm)* Total direct N2O-N emissions from all farm-produced (incl. exported) and imported land-applied manure (kg N2O-N), in year *t*

*N2O-Nmanuredirect(t)* Direct N2O-N emissions from land-applied manure produced on-farm (kg N2O-N), applied to specific fields in year *t*

*N2O-Nmanuredirect\_leftover(t)* Direct N2O-N emissions from farm-produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg N2O-N) in year *t*

*N2O-Nmanuredirect\_export(t)* Direct N2O-N emissions from farm-produced manure exported from the farm (kg N2O-N), in year *t*

### Indirect N2O emissions from land-applied manure

#### Ammonia emissions from farm-produced land-applied manure from beef cattle and dairy cattle

**Beef cattle:** As for NH3 emissions from beef manure during the housing and storage stages, a mass balance model based on the TAN in animal manure is applied to estimate emissions from the land application stage (based on Chai et al., 2014). In western Canada, composted or stockpiled manure is applied onto cropland, pasture and forage land, typically in spring and fall (Sheppard et al., 2011). About 57% of solid manure from Canadian beef farms is assumed to be spread on tilled lands (Bittman et al. 2017). In Holos, the beef manure application strategies considered were solid spread on tilled and no-till (or reduced till) land.

**Dairy cattle:** The mass balance approach described in Chai et al. (2016) used to estimate NH3 emissions from dairy manure during the housing and storage stages is also used to estimate emissions during land application. The manure land application strategies considered were: solid spread on tilled and no-till (or reduced till) land, slurry broadcasting, drop hose banding, shallow injection and deep injection.

The amount of TAN transferred from manure storage to land application is the product of the proportion of available manure applied and the amount of TAN remaining in storage. Ammonia volatilized during land application is calculated by multiplying the applied TAN with the EF specific to the manure type, application practice and the timing of application (**Table 43**).

**Eq. 4.6.2‑1**

where

*ATAlandapplication* Ambient temperature-based adjustments used to correct default NH3 emission factors for land application of solid beef or dairy manure (till, no-till/reduced till spreading) or liquid dairy manure (slurry broadcasting, drop hose banding, shallow injection, deep injection) (1 ≤ ATAlandapplication ≤ 0)[[11]](#footnote-12)

*T* Average daily temperature (°C) for the day that the manure is applied

**Eq. 4.6.2‑2**

where

*EFlandapplication\_adju* Adjusted NH3 EF for land-applied manure(kg NH3-N kg-1 N)

*EFlandapplication* Default NH3 EF for land application for different solid and liquid manure application methods (kg NH3-N kg-1 N) (**Table 43**)

**To calculate NH3 emissions from farm-produced manure applied to a specific field:**

**Eq. 4.6.2‑3**

where

*NH3\_Nmanure\_onfarm(t,field n)* NH3-N loss from land-applied farm-produced solid or liquid beef or dairy cattle manure (kg NH3-N) on field *n* in year *t*, by manure type and manure application method

*fmanuretype(t,field n)* Fraction of farm-produced manure available for land application that is applied to field *n* in year *t*. This is applied to tilled or untilled land during the specified day of application (dimensionless), and is specific to the type of manure applied and the field. *fmanuretype(t,field n)* is calculated as: *Volumemanureremoved / (Total\_Volumelandmanure*\*1000), where: *Volumemanureremoved* = volume of manure removed from storage for application to field *n* on the day of removal (kg), by manure type, calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user); *Total\_Volumelandmanure*= amount of manure available on the day of removal (prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by manure type

*Total\_TANlandmanure* TAN available in stored manure (kg TAN) on the day of removal (prior to removal), by livestock type and manure management system

**Eq. 4.6.2‑4**

where

*TANmanure(t,field n)* Total amount of TAN (kg) in farm-produced manure applied to field *n* in year *t*

*Total\_TANlandmanure(t,field n)* Amount of TAN (kg) in farm-produced manure applied to land in year *t*, specific to the manure type and the field (*n*) to which it was applied, calculated as: *fmanuretype(t,field n) \* Total\_TANlandmanure*

***Any manure not applied to a specific field (‘leftover’ manure) is considered a source of further NH3 emissions. For this purpose, it is assumed that the ‘leftover’ manure is spread equally across the farm’s fields,* meaning that the emission factor is averaged across all available fields weighted by their area.**

**To calculate NH3 emissions from the application of leftover manure on the farm’s fields:**

**Eq. 4.6.2‑5**

where

Emission factor for leftover manure TAN applied across the farm’s fields, calculated as an average across all available fields (excl. native rangeland, if present), weighted by their area (kg NH3-N kg-1 N)

**Eq. 4.6.2‑6**

where

*TANlandmanureremaining(t)* Available TAN in stored manure minus manure TAN applied to specific fields or exported (kg N)

*Total\_TANlandmanure(t)* Total TAN available in stored manure (kg TAN) in year *t*, by livestock type and manure management system

*TANmanure,allfields(t)* Total amount of farm-produced manure TAN (kg) applied to all fields in year *t*

*Total\_TANmanure\_export(t)* Total N (kg N) exported as manure in year *t*, calculated using **Eq. 4.6.2‑10**

**Eq. 4.6.2‑7**

where

*NH3\_Nmanure\_leftover(t)* NH3-N emissions (kg NH3-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland, if present) in year *t*

**Eq. 4.6.2‑8**

where

*NH3\_Nmanure\_leftover(t,field n)* NH3 emissions (kg NH3-N) from the application of ‘leftover’ stored manure to field *n* in year *t*

**Eq. 4.6.2‑9**

*TANmanuretype\_export(t)* Total amount of TAN exported from the farm in farm-produced manure (kg N) in year *t*, specific to the manure type

*Total\_TANlandmanure(t)* Total TAN available in stored manure for land application, addition to an AD system or export (kg N) in year *t*, by livestock type and manure management system

*Volumemanureremoved(t)* Volume of each type of manure removed from storage for export (kg) in year *t*, specific to the manure type

*Total\_Volumelandmanure(t)* Amount of each type of manure available in year *t* (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

**Eq. 4.6.2‑10**

where

*Total\_TANmanure\_export(t)* Total TAN exported from the farm in manure (kg N) in year *t*

**Eq. 4.6.2‑11**

where

*NH3\_Nmanure\_export(t,farm)* NH3-N emissions (kg NH3-N) calculated for exported manure (as if applied) in year *t*

#### Ammonia emissions from farm-produced land-applied manure from broilers, layers and turkeys

For broilers, layers and turkeys, the same general approach to estimate NH3 emissions from land-applied manure that we employed for beef and dairy cattle is used. The amount of TAN transferred from manure storage to land application is the product of the proportion of available manure applied and the amount of TAN remaining in storage. As for cattle, NH3-N volatilized during land application is calculated by multiplying the applied TAN with the temperature-dependent EF (see box below). To estimate NH3-N emissions from manure applied to specific fields, ‘leftover’ manure applied across the farm’s fields (excl. native rangeland) and exported manure, see Section 4.6.2.1.

**Ammonia emissions from land application of manure are calculated on a daily basis.**

Holos V4 will use the following default values for the fraction of excreted uric acid/TAN emitted as NH3 during land application of manure for broilers, layers and turkeys:

if T ≥15, then 0.85

if 15 > T > 10, then 0.73

if 10 > T ≥ 5, then 0.35

if T < 5, then 0.25

where: T is the average daily temperature (°C) for the day that manure is applied

Original source: Brentrup et al. (2000)

#### Ammonia emissions from farm-produced land-applied manure from sheep, swine and other livestock

The estimation of NH3-N emissions during the land application of manure from sheep, swine, poultry (other than broilers, layers and turkeys) and other livestock are estimated using the amount of total manure N available in storage and default *Fracvolatilization* values for the application of manure N fertilizer from ECCC (2022) for swine (**Table 62**), which are year- and province-specific, and a default IPCC (2019) *Fracvolatilization* value for organic N fertilizers from IPCC (2019) for sheep and other livestock (**Table 36**).

**To calculate NH3 emissions from farm-produced manure applied to a specific field:**

**Eq. 4.6.2‑12**

where

*NH3-Nmanure\_onfarm(t, field n)* NH3-N loss from land-applied farm-produced manure from sheep, swine or other livestock (kg NH3-N) on field *n* in year *t*

*fmanuretype(t,field n)* Fraction of farm-produced manure available for land application applied to field *n* in year *t*. This is applied to tilled or untilled land during the specified day of application (dimensionless), and is specific to the type of manure applied and the field. *fmanuretype(t,field n)* is calculated as: *Volumemanureremoved / (Total\_Volumelandmanure*\*1000), where: *Volumemanureremoved* = volume of manure removed from storage for application to field *n* on the day of removal (kg), by manure type, calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user); *Total\_Volumelandmanure*= amount of manure available on the day of removal (prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by manure type

*Total\_Nlandmanure* N available in stored manure (kg N) on the day of removal (prior to removal), by livestock type and manure management system

*Fracvolatilization\_landapplication* Fraction of land-applied manure N lost by volatilization (kg NH3-N (kg N)-1); for land-applied manure from all storage systems. For swine, year- and province-specific default values for the application of manure N are used (**Table 62**); for sheep and other livestock the value of 0.21 kg NH3-N (kg-1) N for pasture/range/paddock is used (**Table 36**)

**Eq. 4.6.2‑13**

where

*Nmanure\_onfarm(t,field n)* Total amount of N (kg) in farm-produced manure applied to field *n* in year *t*, by livestock type

*Total\_Nlandmanure(t,field n)* Amount of N in stored manure (kg N) applied to field *n* in year *t*, specific to the livestock type and manure management system, calculated as: *fmanuretype(t,field n) \* Total\_Nlandmanure(t)*

***Any manure not applied to a specific field (‘leftover’ manure) is considered a source of further NH3 emissions. For this purpose, it is assumed that the ‘leftover’ manure N is spread equally across the farm’s fields (excl. native rangeland, if present),* with NH3 emissions estimated using the same *Fracvolatilization\_landapplication* values used in Eq. 4.6.2‑12. Emissions from the application of leftover manure are estimated on a per field basis using the same approach employed for cattle and poultry. To calculate NH3 emissions from the application of leftover manure on the farm’s fields:**

**Eq. 4.6.2‑14**

where

*Nlandmanureremaining(t)* Stored manure N available for application to land minus stored manure N applied to specific fields or exported (kg N) in year *t*

*Total\_Nlandmanure(t)* Total N available in farm-produced stored manure (kg N) in year *t*, by livestock type and manure management system

*Nmanure\_onfarm,allfields(t)* Total amount of farm-produced manure N (kg) applied to specific fields in year *t*

*Total\_Nmanure\_export(t)* Total N (kg N) exported from the farm as manure in year *t*

**Eq. 4.6.2‑15**

where

*NH3\_Nmanure\_leftover(t)* NH3-N emissions (kg NH3-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland, if present) in year *t*

*Nlandmanureremaining(t)* Stored manure N available for application to land minus manure N applied to specific fields or exported (kg N) in year *t*

**Eq. 4.6.2‑16**

where

*NH3\_Nmanure\_leftover(t,field n)* NH3 emissions (kg NH3-N) from the application of ‘leftover’ stored manure to field *n* in year *t*

**Eq. 4.6.2‑17**

where

*Nmanuretype\_export(t)* Total amount of N exported from the farm in farm-produced manure (kg N) in year *t*, specific to the manure type

*Total\_Nlandmanure(t)* Total N available for land application, addition to an AD system or export (kg N) in year t, by livestock type and manure management system

*Volumemanureremoved(t)* Volume of each type of manure removed from storage for export (kg) in year t, specific to the manure type

*Total\_Volumelandmanure(t)* Amount of each type of manure available in year t (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

**Eq. 4.6.2‑18**

*Total\_Nmanure\_export(t)* Total N exported from the farm in manure (kg N) in year *t*

**Eq. 4.6.2‑19**

*NH3\_Nmanure\_export(t,farm)* NH3-N emissions (kg NH3-N) calculated for exported manure (as if applied) in year *t*

**Note:** In the estimation of NH3-N emissions from exported manure, emissions are first calculated for each type of exported manure (e.g., beef cattle solid storage (stockpiled)), and these emissions are then summed to estimate the total NH3-N emissions from all manure exported from the farm (as if applied). Therefore, in this equation, the *Fracvolatilization\_landapplication* value used is livestock and manure type-specific.

#### Ammonia emissions from imported land-applied manure for all livestock types

To estimate NH3 emissions from the land application of imported manure (and subsequently indirect N2O emissions via volatilization), we cannot use the approach described in **sections 4.6.2.1** (for beef and dairy cattle) and **4.6.2.2** (for poultry), as this is based on the amount of TAN in manure available for application to land, which is not known when the manure is imported. Therefore, in the case of imported manure, we use the approach adopted by the National Inventory Report (ECCC, 2022), and used in Section 4.6.2.3 for the estimation of NH3 emissions from the land application of farm-produced manure from sheep, swine and other livestock.

**Eq. 4.6.2‑20**

where

*NH3\_Nmanure\_imported(t,field n)* NH3-N emissions from imported manure applied (kg NH3-N) to field *n* in year *t*

*Nlandmanuretype\_imported(t,field,n)* N applied to land in imported manure, calculated as: kg manure applied (user-defined) \* manure N content (%, manure type-specific from **Table 6**) on field *n* in year *t*

*Fracvolatilization\_landapplication* Fraction of land-applied manure that is volatilized (kg NH3-N (kg-1) manure N applied) (**Table 61** (for dairy cattle), **Table 62** (for swine), 0.21 kg NH3-N (kg-1) N for all other livestock types)

**Note:** In the estimation of NH3-N emissions from imported manure, emissions are first calculated for each type of imported manure (e.g., beef cattle solid storage (stockpiled)), and these emissions are then summed to estimate the total NH3-N emissions from all manure imported to the farm (as if applied). Therefore, in this equation, the *Nlandmanuretype\_imported(t,field n)* value and the *Fracvolatilization\_landapplication* value used are livestock and manure type-specific.

#### Total NH3 emissions during land application of farm-produced and imported manure and from exported manure

**To estimate total NH3-N losses from a specific field following manure application:**

**Eq. 4.6.2‑21**

where

*NH3\_Nallmanure(t,field n)* Total NH3-N emissions from farm-produced and imported land-applied manure (kg NH3-N), specific to field *n* in year *t*

*NH3\_Nmanure\_onfarm(t,field n)* NH3-N emissions from land-applied manure produced on-farm (kg NH3-N), applied to field *n* in year *t*

*NH3\_Nmanure\_leftover(t,field n)* NH3-N emissions from farm produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg NH3-N), specific to field *n* in year *t*

*NH3\_Nmanure\_imported(t,field n)* NH3-N emissions from imported land-applied manure (kg NH3-N), specific to field *n* in year *t*

**To estimate total NH3-N losses from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.2‑22**

where

*NH3\_Nallmanure(t,farm)* Total NH3-N emissions from all farm-produced (incl. exported) and imported land-applied manure (kg NH3-N), in year *t*

*NH3\_Nmanure\_onfarm(t)* NH3-N emissions from land-applied manure produced on-farm (kg NH3-N), applied to specific fields in year *t*

*NH3\_Nmanure\_leftover(t)* NH3-N emissions from farm-produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg NH3-N), in year *t*

*NH3\_Nmanure\_export(t)* NH3-N emissions from exported manure (as if applied) (kg NH3-N), in year *t*

*NH3\_Nmanure\_imported(t)* NH3-N emissions from imported land-applied manure (kg NH3-N), in year *t*

**Ammonia emissions from the land application of manure are calculated on a daily basis.**

### Nitrous oxide volatilization from manure following land application

#### Nitrous oxide emissions via volatilization during land application of farm-produced and imported manure and from exported manure

**To calculate indirect N2O emissions from volatilization from farm-produced manure applied to a specific field, for all livestock types:**

**Eq. 4.6.3‑1**

Derived from IPCC 2019, Eq. 11.9

where

*N2O-Nmanurevolatilization\_onfarm(t,field n)* Indirect N2O-N emissions via volatilization following land application of farm-produced manure (kg N2O-N) on field *n* in year *t*

*NH3-Nmanure\_onfarm(t,field n)* NH3-N loss from land-applied farm-produced manure (kg NH3-N) on field *n* in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**)

**Eq. 4.6.3‑2**

Derived from IPCC 2019, Eq. 11.9

where

*N2O-Nmanurevolatilization\_onfarm(t,field n)* Indirect N2O-N emissions via volatilization following land application of farm-produced manure (lg N2O-N) on field *n* in year *t*

*NH3\_Nmanure\_leftover(t,field n)* NH3 emissions (kg NH3-N) from the application of ‘leftover’ stored manure to field n in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**)

**Eq. 4.6.3‑3**

Derived from IPCC 2019, Eq. 11.9

where

*N2O-Nmanurevolatilization\_export(t,farm)* Indirect N2O-N emissions via volatilization (kg N2O-N) calculated for exported manure (as if applied) in year *t*

*NH3\_Nmanure\_export(t,farm)* NH3-N emissions from farm-produced manure exported from the operation (kg NH3-N), in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**)

**Eq. 4.6.3‑4**

Derived from IPCC 2019, Eq. 11.9

*N2O-Nmanurevolatilization\_imported(t,field n)* Indirect N2O-N emissions via volatilization following land application of imported manure (kg N2O-N) on field *n* in year *t*

*NH3\_Nmanure\_imported(t,field n)* NH3-N emissions from imported manure (kg NH3-N) applied to field *n* in year *t*

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N volatilized)-1] (**Table 36**)

#### Total indirect N2O emissions via volatilization from manure during land application

**To estimate total indirect N2O-N losses via volatilization from a specific field following manure application:**

**Eq. 4.6.3‑5**

where

*N2O-Nallmanurevolatilization(t,field n)* Total N2O-N emissions from stored and imported manure (kg N2O-N), applied to field *n* in year *t*

*N2O-Nmanurevolatilization\_onfarm(t,field n)* N2O-N emissions from land-applied manure produced on-farm (kg N2O-N), applied to field *n* in year *t*

*N2O-Nmanurevolatilization\_leftover(t,field n)* N2O-N emissions from farm-produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg N2O-N), specific to field *n* in year *t*

*N2O-Nmanurevolatilization\_imported(t,field n)n)* N2O-N emissions from imported land-applied manure (kg N2O-N), specific to field *n* in year *t*

**To estimate total indirect N2O-N losses via volatilization from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.3‑6**

where

*N2O-Nallmanurevolatilization(t)* Total N2O-N emissions from farm-produced (incl. exports) and imported land-applied manure (kg N2O-N), in year *t*

*N2O-Nmanurevolatilization\_onfarm(t)* N2O-N emissions from land-applied manure produced on-farm (kg N2O-N), applied to specific fields in year *t*

*N2O-Nmanurevolatilization\_leftover(t)* N2O-N emissions from farm-produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg NH3-N), in year *t*

*N2O-Nmanurevolatilization\_export(t)* N2O-N emissions from farm-produced exported manure (as if applied) (kg N2O-N), in year *t*

*N2O-Nmanurevolatilization\_imported(t)* N2O-N emissions from imported land-applied manure (kg N2O-N), in year *t*

**Indirect N2O emissions from land application of livestock manure are calculated on a daily basis.**

#### Adjustment of NH3 volatilization estimates from land application of manure following indirect N2O emissions

As for NH3 emissions from manure during the housing and manure storage stages, the NH3 emissions following land application of farm-produced and imported manure need to be adjusted to avoid double-counting of subsequent indirect N2O-N losses.

**Eq. 4.6.3‑7**

where

*NH3\_Nmanure\_onfarm(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of farm-produced manure (kg NH3-N) on field *n* in year *t*

**Eq. 4.6.3‑8**

where

*NH3\_Nmanure\_leftover(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of farm-produced manure (kg NH3-N) on field *n* in year *t*

**Eq. 4.6.3‑9**

where

*NH3\_Nmanure\_export(t,farm)\_adju* Adjusted daily NH3-N emissions (kg NH3-N) from exported manure (as if applied) in year *t*

**Eq. 4.6.3‑10**

where

*NH3\_Nmanure\_imported(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of imported manure (kg NH3-N) on field *n* in year *t*

**Adjusted ammonia emissions from land application of manure are calculated on a daily basis.**

#### Total adjusted NH3 emissions during land application of farm-produced and imported manure and from exported manure

**To estimate total adjusted NH3-N losses from a specific field following manure application:**

**Eq. 4.6.3‑11**

where

*NH3\_Nallmanure(t,field n)\_adju* Total adjusted NH3-N emissions from farm-produced and imported land-applied manure (kg NH3-N), specific to field *n* in year *t*

*NH3\_Nmanure\_onfarm(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of farm-produced manure (kg NH3-N) on field *n* in year *t*

*NH3\_Nmanure\_leftover(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of farm-produced manure (kg NH3-N) on field *n* in year *t*

*NH3\_Nmanure\_imported(t,field n)\_adju* Adjusted daily NH3-N emissions following land application of imported manure (kg NH3-N) on field *n* in year *t*

**To estimate total adjusted NH3-N losses from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.3‑12**

where

*NH3\_Nallmanure(t,farm)\_adju* Total adjusted NH3-N emissions from all farm-produced and imported land-applied manure sourced (kg NH3-N), in year *t*

*NH3\_Nmanure\_onfarm(t)\_adju* AdjustedNH3-N emissions from land-applied manure produced on-farm (kg NH3-N), applied to specific fields in year *t*

*NH3\_Nmanure\_leftover(t)\_adju* AdjustedNH3-N emissions from farm-produced leftover manure applied equally across all of the farm’s fields (except native rangeland) (kg NH3-N), in year *t*

*NH3\_Nmanure\_export(t)\_adju* AdjustedNH3-N emissions from exported manure (as if applied) (kg NH3-N), in year *t*

*NH3\_Nmanure\_imported(t)\_adju* AdjustedNH3-N emissions from imported land-applied manure (kg NH3-N), in year *t*

### Indirect N losses from land-applied manure via leaching and runoff

**For all livestock types:**

**Eq. 4.6.4‑1**

Derived from IPCC 2019

where

*N2O-Nmanureleach(t,field n)* Indirect N2O emissions via leaching and runoff from farm-produced and imported manure applied to land (kg N2O-N) on field *n* in year *t*

*Nmanure(t, field n)* Total amount of farm-produced and imported manure N (kg) applied to field *n* in year *t*

*Fracleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* Emission factor for leaching [kg N2O-N (kg N)-1], see box below

Holos V4 will use the following constant value:

*EFleach* 0.011 (IPCC 2019)

***Any manure not applied to a specific field (‘leftover’ manure) is considered a further source of indirect N2O emissions via leaching/runoff. For this* purpose*, it is assumed that the ‘leftover’ manure is spread equally across the farm’s fields (excl. native rangeland, if present)*.**

**Eq. 4.6.4‑2**

where

*N2O-Nmanureleach\_leftover(t,field n)* Indirect N2O emissions via leaching and runoff (kg N2O-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) on field *n* in year *t*

**Eq. 4.6.4‑3**

*N2O-Nmanureleach\_export(t,farm)* Indirect N2O emissions via leaching and runoff (kg N2O-N) from exported manure (as if applied) in year *t*

**To estimate total N2O-N losses via leaching from a specific field following manure application:**

**Eq. 4.6.4‑4**

where

*N2O-Nallmanure(t,field n)* Total N2O-N emissions via leaching and runoff from farm-produced and imported land-applied manure (kg N2O-N), specific to field *n* in year *t*

*N2O-Nmanureleach(t,field n)* Indirect N2O emissions via leaching and runoff from farm-produced and imported manure applied to land (kg N2O-N) on field *n* in year *t*

*N2O-Nmanureleach\_leftover(t,field n)* Indirect N2O emissions via leaching and runoff (kg N2O-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) on field *n* in year *t*

**To estimate total N2O-N losses via leaching from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.4‑5**

where

*N2O-Nallmanure(t,farm)* Total N2O-N emissions via leaching and runoff from farm-produced (incl. exported) and imported land-applied manure (kg N2O-N), in year *t*

*N2O-Nmanureleach(t)* Indirect N2O emissions via leaching and runoff from farm-produced and imported manure applied to land (kg N2O-N) in year *t*

*N2O-Nmanureleach\_leftover(t)* Indirect N2O emissions via leaching and runoff (kg N2O-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) in year *t*

*N2O-Nmanureleach\_export(t)* Indirect N2O emissions via leaching and runoff (kg N2O-N) from exported manure (as if applied) in year *t*

**To calculate the actual amount of N leached:**

**Eq. 4.6.4‑6**

Derived from IPCC 2019

where

*NO3-Nmanureleach(t,field n)* NO3 emissions via leaching and runoff from farm-produced and imported manure applied to land (kg NO3-N) on field *n* in year *t*

*Nmanure(t, field n)* Total amount of farm-produced and imported manure N (kg) applied to field *n* in year *t*

*Fracleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* Emission factor for leaching [kg N2O-N (kg N)-1], see box below

***Any manure not applied to a specific field (‘leftover’ manure) is considered a further source of indirect N2O emissions via leaching/runoff. For this* purpose*, it is assumed that the ‘leftover’ manure is spread equally across the farm’s fields (excl. native rangeland, if present)*.**

**Eq. 4.6.4‑7**

where

*NO3-Nmanureleach\_leftover(t,field n)* NO3 emissions via leaching and runoff (kg NO3-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) on field *n* in year *t*

**Eq. 4.6.4‑8**

*NO3-Nmanureleach\_export(t,farm)* NO3 emissions via leaching and runoff (kg NO3-N) from exported manure (as if applied) in year *t*

**To estimate total NO3-N losses via leaching from a specific field following manure application:**

**Eq. 4.6.4‑9**

where

*NO3-Nmanureleach(t,field n)* NO3 emissions via leaching and runoff from farm-produced and imported manure applied to land (kg NO3-N) on field *n* in year *t*

*NO3-Nmanureleach\_leftover(t,field n)* NO3 emissions via leaching and runoff (kg NO3-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) on field *n* in year *t*

**To estimate total NO3-N losses via leaching from the farm, including emissions from exported manure (as if applied):**

**Eq. 4.6.4‑10**

where

*NO3-Nmanureleach(t,farm)* NO3 emissions via leaching and runoff from farm-produced and imported manure applied to land (kg NO3-N) on field *n* in year *t*

*NO3-Nmanureleach(t)* NO3 emissions via leaching and runoff from farm-produced and imported manure applied to land (kg NO3-N) in year *t*

*NO3-Nmanureleach\_leftover(t)* NO3 emissions via leaching and runoff (kg NO3-N) from the application of ‘leftover’ stored manure to the farm’s fields (excl. native rangeland) in year *t*

*NO3-Nmanureleach\_export(t)* NO3 emissions via leaching and runoff (kg NO3-N from exported manure (as if applied) in year *t*

### Total indirect N2O emissions from land-applied manure

**Eq. 4.6.5‑1**

where

*N2Omanuremanure* Total indirect N2O emissions from farm-produced (incl. exported) and imported livestock manure applied to land (kg N2O-N)

### Total N2O emissions from land-applied manure

**Eq. 4.6.6‑1**

where

*N2O-Nmanuresoils* Total direct and indirect N2O-N emissions from land application of farm-produced (incl. exported) and imported manure (kg N2O-N)

## Manure **C and N for the** ICBM/IPCC Tier 2 and soil N2O models

(by S.J. Pogue)

This section describes the calculations used to estimate the amount of C and N added to the soil in land-applied manure, as well as the amount of water available in land-applied manure. The amount of C entering the soil C pool serves as input to the IPCC Tier 2 soil C model and the ICBM in Holos; the amount of N entering the soil N pool serves as input to the model (adapted from Liang et al. 2020) used for the multi-year estimation of soil N2O emissions. The amount of C and N added to the relevant soil pools account for any land application losses.

### Carbon

To estimate manure C applied to soil in field *n* in year *t*:

**Eq. 4.7.1‑1**

where

*Cmodel\_manuretype(t,field n)* Amount of C added to the soil in farm-produced manure (kg C) applied to field *n* in year *t*, by livestock type and manure management system

*fmanuretype(t,field n)* Fraction of farm-produced manure available for land application that is applied to field *n* in year *t*. This is applied to tilled or untilled land during the specified day of application (dimensionless), and is specific to the type of manure applied and the field. *fmanuretype(t,field n)* is calculated as: *Volumemanureremoved / (Total\_Volumelandmanure*\*1000), where: *Volumemanureremoved* = volume of manure removed from storage for application to field *n* on the day of removal (kg), by manure type, calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user); *Total\_Volumelandmanure*= amount of manure available on the day of removal (prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by manure type

*Total\_Cstorage(t)* Total C available in stored manure (kg C), by livestock type and manure management system in year *t*, calculated using **Eq. 4.1.3‑16**

*Cimported(t,field n)* C added to the soil C pool in imported manure (kg C), by manure type and specific to field *n* in year *t*

**Eq. 4.7.1‑2**

where

*Cmodel\_manure(t,field n)* Total amount of C added to the soil C pool (kg C) in stored and imported manure, specific to field *n* in year *t*

*Cmodel\_manuretype(t,field n)* Amount of C added to the soil C pool (kg C) in stored and imported manure, by manure type and specific to field *n* in year *t*

***Any manure not applied to a specific field (‘leftover’ manure) is spread equally across all of the farm’s fields (excl. native rangeland, if present)*.**

**Eq. 4.7.1‑3**

where

*Cmodel\_landmanureremaining(t)* Remaining manure C available for addition to the soil C pool minus manure C applied to specific fields or exported (kg C) in year *t*

*Cmodel,allfields(t)* Total amount of C in stored manure (kg C) applied to specific fields in year *t*

*Total\_Cexport(t)* Total amount of C in exported manure (kg C) in year *t*

**Eq. 4.7.1‑4**

where

*Cmodel\_landmanureremaining(t,field n)* Remaining manure C added to the soil C pool (kg C), specific to field *n* in year *t*

**Eq. 4.7.1‑5**

where

*Cmanuretype\_export(t)* Total amount of C exported from the farm in stored manure (kg N) in year *t*, specific to the manure type

*Total\_Cstorage(t)* Total C available in stored manure (kg C), by livestock type and manure management system, in year *t*, calculated using **Eq. 4.1.3‑16**

*Volumemanureremoved(t)* Volume of each type of manure removed from storage on the day of removal (kg) for export, specific to the manure type

*Total\_Volumelandmanure(t)* Amount of each type of manure available on the day of removal (prior to removal) (1000 kg wet weight for solid manure and 1000 L for liquid manure day-1 – we assume that 1 kg of liquid manure = 1 L of liquid manure), by livestock type and manure management system, calculated using **Eq. 4.5.3‑3**

**Eq. 4.7.1‑6**

where

*Total\_Cmodel\_manure(t,field n)* Total amount of C added to the soil C pool (kg C) in all field-applied manure, specific to field *n* in year *t*

### Nitrogen

To estimate manure N applied to soil (after all land application N losses) in field *n*:

**Eq. 4.7.2‑1**

where

*Total\_Nmodel\_manure(t,field n*) Total amount of N added to the soil N pool (kg N) in all field-applied manure, specific to field *n* in year *t*

*Nmanure(t,field n)* Total amount of farm-produced and imported manure N (kg) applied to field *n* in year *t****,*** calculated using **Eq. 4.6.1‑2**

*Nlandmanureremaining(t,field n)* Total amount of leftover manure N (kg) applied to field *n* in year *t*

*N2O-Nallmanuredirect(t,field n)* Total direct N2O emissions (kg N2O-N) from the application of all stored and imported manure on field *n* in year *t*, calculated using **Eq. 4.6.1‑10**

*NH3\_Nallmanure(t,field n)* Total NH3-N emissions from farm-produced and imported land-applied manure (kg NH3-N), specific to field *n* in year *t*, calculated using **Eq. 4.6.2‑21**

*N2O-Nallmanureleach(t,field n)* Total N2O-N emissions via leaching and runoff from farm-produced and imported land-applied manure (kg N2O-N), specific to field *n* in year *t*, calculated using **Eq. 4.6.4‑4**

*NO3-Nallmanureleach(t,field n)* NO3 emissions via leaching and runoff from farm-produced and imported manure applied to land (kg NO3-N) on field *n* in year *t*, calculated using **Eq. 4.6.4‑9**

### Water

**Eq. 4.7.3‑1**

where

*Watermanuretype(t,field n)* Amount of water in land-applied manure (mm ha-1), specific to field *n* in year *t*

*Manureamount(t,field n)* Amount of manure applied to field *n* in year *t* (kg ha-1), specified by user, specific to the manure type

*moisturecontent*  Moisture content of the applied manure (%) (**Table 6**)

**Eq. 4.7.3‑2**

where

*Watermanure(t,field n)* Total amount of water in land-applied manure (mm), specific to field *n* in year *t*

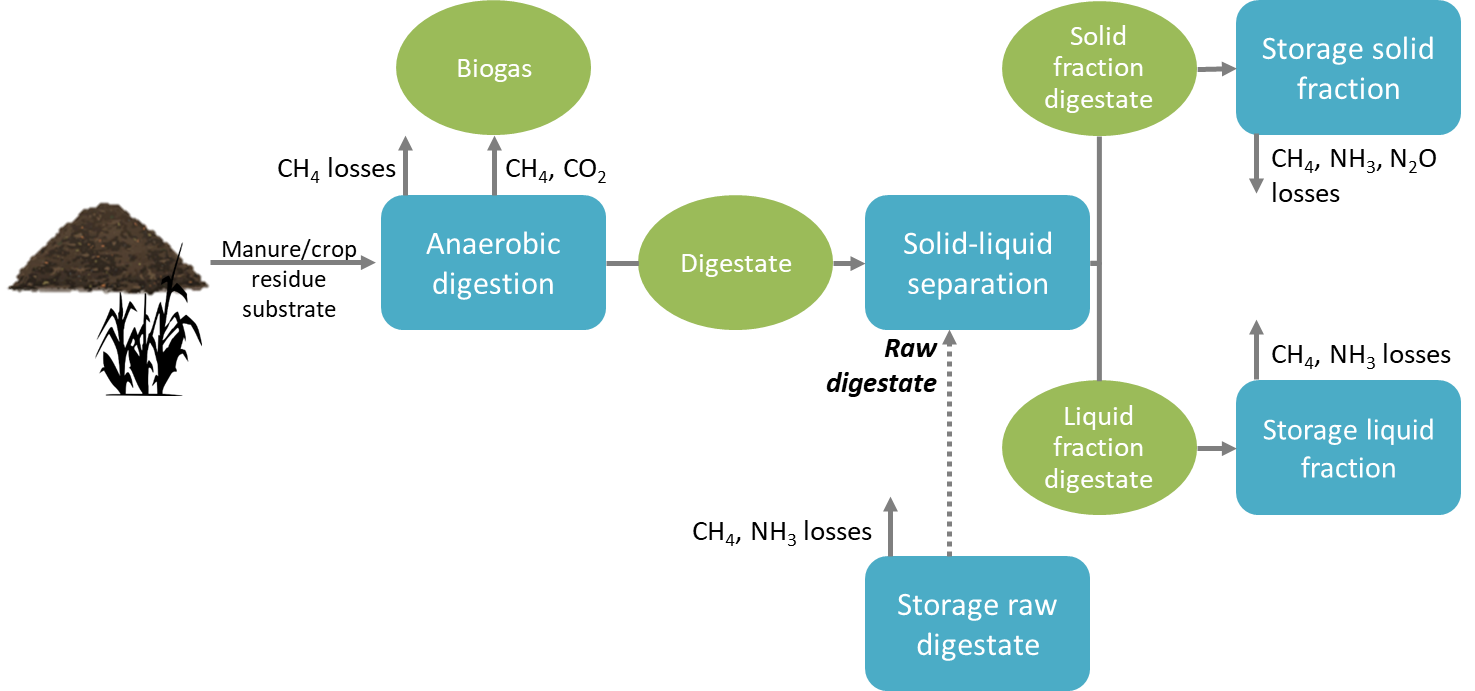
## Anaerobic digestion of livestock manure and crop residues

(by C. Vaneeckhaut and S.J. Pogue)

The anaerobic digestion (AD) component in Holos has the following assumptions:

* The system is a wet anaerobic continuously stirred tank reactor (CSTR)
* The primary feedstock is livestock manure with an optional co-feedstock of crop residues
* Biogas valorisation: combined heat and power (CHP) or direct injection to the gas grid
* Digestate treatment: solid-liquid separation

The overall structure of the AD component is presented in **Figure 4**.



**Figure 4.** Flow diagram representing the structure of the anaerobic digestion component in Holos. Blue boxes represent unit processes; green pools represent valorisable substrates and products; arrows represent nutrient and C flows.

Emissions of CH4 and CO2 from the AD process are estimated based on mass balance principles and first order kinetics. The substrate entering the anaerobic digester can be livestock manure, crop residues, or a combination of livestock manure and crop residues.

The flow of VS, total N (TN), TAN, ON and total C (TC) entering the AD system depends on the amount of substrate entering the system, its VS, TN, TAN, ON and TC content, and the amount of time the manure is stored before entering the digester, where applicable. For raw/fresh manure that is added to the digester on the day it is produced (excreted), we assume that the concentrations of VS, nutrients and C are equal to the concentrations excreted by the animal minus any housing losses. For raw/fresh manure, the user specifies the percentage of manure produced daily that is added to the AD system, after housing C and N losses but before the manure enters storage. All calculations should be completed for each animal group and manure management system.

For liquid manure that is stored for a period of time prior to entering the digester, the amount of VS consumed during the pre-digester storage period is estimated using the approach described in **section 4.1.3**. For solid manure, a fixed reduction factor is applied to excreted VS, based on reported reductions in biomethane potential (BMP) during different solid manure storage methods (see **Table 45**). The kinetic rate of degradation of manure (*khydr,i*) also significantly reduces with age. The concentration of N and C at the end of this initial pre-digester storage period is estimated based on initial amounts in raw manure minus any housing and storage losses for both solid and liquid manure. For manure that is stored prior to being added to the AD system, the user specifies the percentage of manure that is available in storage that is added to the digester, i.e., the percentage of the stored manure ‘stock’ that is removed from storage and added to the AD system, by animal group and manure management system.

For crop residues, default values for VS, nutrient and C concentrations are estimated based on data for total solid (TS) content (%) and VS content (% of TS) derived from the literature (**Table 46**).

### Flow of substrate, VS, N and C into the digester

#### For fresh/raw livestock manure entering the digester

The model user has the option to add ‘fresh’ or ‘raw’ manure to the AD system – this includes both solid and liquid manure types. This type of manure or AD substrate refers to faeces and urine excreted by the animal + bedding that is removed from the housing system and added to the digester before the material enters a manure storage system. Losses of C and N that occur during the housing stage are subtracted from this substrate before it enters the digester. Currently, in Holos V4, the option to add fresh/raw manure to an AD system is possible only for beef cattle and dairy cattle, as the model does not currently estimate C and N losses for the housing and storage stages separately for most other livestock groups (e.g., sheep, swine, etc.).

***Flow of total mass of substrate entering the digester***

**Eq. 4.8.1‑1**

where

*Fflow\_substrate,fm* Flow rate of fresh manure entering the digester (kg or L day-1 – we assume that 1kg of liquid manure = 1 L of liquid manure)

*Fflow\_substrate,fm,i* Flow rate of fresh manure type *i* entering the digester (kg or L day-1) – this includes excreted faeces and urine + bedding

**Eq. 4.8.1‑2**

where

*Nexcretion,fm,i* N excreted (kg N day-1), by animal group, calculated using **Eq. 4.2.1‑29**

*Ncontent,fm,i* N content of excreta (urine + faeces; % wet weight) (**Table 6**) – for fresh manure entering the AD system, the *Ncontent* values for ‘Manure (urine + feces) deposited on pasture’ are used for beef and dairy cattle manure

*Beddingappl\_rate*Bedding application rate (kg head-1 day-1), by animal group (user specified or calculated using the Bedding Application Calculator)

*#animals* Number of animals, by animal group

*ManureADproportion,fm,i* Proportion of total manure produced daily added from the housing system to the AD system, calculated as: Daily percentage of manure added (%, user-defined) / 100, by animal group and manure management system; this includes faeces/urine excreted + bedding

***Flow of TS entering the digester***

**Please note:** for all manure substrate types (fresh and stored) entering the digester, it is not necessary to estimate the TS flow as this is not used in any subsequent equations. Therefore, in **Table 46**, the TS value for all manure types is zero.

**Eq. 4.8.1‑3**

where

*TSflow\_substrate,fm* Flow rate of TS in substrate entering the digester from fresh manure (kg day-1)

*TSsubstrate,fm,i* Total solids concentration of substrate *i* (kg t-1) (**Table 46**)

***Flow of VS entering the digester***

**Eq. 4.8.1‑4**

where

*VSflow\_substrate,fm,i* Flow rate of VS entering the digester in fresh manure (kg day-1), by animal group and housing/manure management system

*VS* Volatile solids excreted (kg head-1 day-1), by animal group for beef and dairy cattle, calculated using **Eq. 4.1.2‑1**

*#animals* Number of animals, by animal group

***Flow of total N entering the digester***

**Eq. 4.8.1‑5**

where

*Nflow\_substrate,fm,i* Flow rate of total N in fresh manure (incl. bedding) entering the digester (kg N day-1), by animal group and housing/manure management system

*Nexcretion,fm,i* Total amount of N excreted (kg N day-1), by animal group and housing/manure management system, calculated using **Eq. 4.2.1‑29**

*Nbedding,fm,i* Total amount of N added from bedding materials (kg N day-1), by animal group and housing/manure management system, calculated using **Eq. 4.2.1‑32**

*N2O-Ndirectmanure,fm,i* Direct N2O emissions (kg N2O-N day-1) from manure during the housing stage, by animal group and housing/manure management system, calculated using **Eq. 4.2.2‑2**

*NH3\_Nhousing,fm,i* Daily NH3-N (kg NH3-N day-1) emissions from housing, by animal group and housing/manure management system; calculated using **Eq. 4.3.1‑11** (confined no barn housing for beef and dairy cattle) and **Eq. 4.3.1‑15** (barn housing for beef cattle)

***Flow of organic N entering the digester***

**For beef and dairy cattle:**

**Eq. 4.8.1‑6**

where

*OrganicNflow\_substrate,fm,i* Flow rate of organic N (kg N day-1 ) in fresh manure (incl. bedding) entering the digester, by animal group and housing/manure management system

*OrganicNmanure,fm,i* Daily organic N in fresh manure (kg N day-1), by animal group and housing/manure management system, calculated using **Eq. 4.3.1‑7** for beef and dairy cattle

**Please note:** equations relating to the estimation of C and N flows for broilers, layers and turkeys are included in this section, although these are not currently incorporated into the Holos model calculations due to a lack of necessary data. Thus it is not currently possible to add fresh/raw manure for these poultry groups to an AD system in the model interface. This option could be available in future versions of Holos.

**~~For broilers, layers and turkeys:~~**

**~~Eq. 4.8.1‑7~~**

~~where~~

*~~OrganicN~~~~flow\_substrate,fm,i~~*~~Flow rate of organic N (kg N day~~~~-1~~ ~~) in fresh manure entering the digester, by animal group and housing/manure management system~~

*~~N~~~~excretion,fm,i~~* ~~Total amount of N excreted (kg N day~~~~-1~~~~), by animal group and housing/manure management system, calculated using~~ **~~Eq. 4.2.1‑29~~**

*~~TAN~~~~excretion,fm,i~~*~~Total ammonical N (TAN) excretion rate (kg TAN head~~~~-1~~ ~~day~~~~-1~~~~).~~~~For broilers, layers and turkeys, default~~ *~~TAN~~~~excretion~~~~\_rate~~* ~~values are used (see Box associated with~~ **~~Eq. 4.3.3‑5~~**~~)~~

*~~#animals~~* ~~Number of animals (broilers, layers or turkeys)~~

***Flow of TAN entering the digester***

**Eq. 4.8.1‑8**

where

*TANflow\_substrate,fm,i* Flow rate of TAN in fresh manure (incl. bedding) entering the digester (kg N day-1), by animal group and housing/manure management system

*TANflowstorage,fm,i* TAN flowing from housing to storage, i.e., TAN excreted minus housing NH3-N losses, by animal group and housing/manure management system, calculated using **Eq. 4.3.2‑1** for beef and dairy cattle

***Flow of total C entering the digester***

**Eq. 4.8.1‑9**

where

*Cflow\_substrate,fm,i* Flow rate of total C in fresh manure (incl. bedding) entering the digester (kg day-1), by animal group and housing/manure management system

*Cflowstorage,fm,i* Total amount of C flowing into storage each day (minus housing CH4-C emissions), by animal group and housing/manure management system, calculated using **Eq. 4.1.3‑14**

#### For crop residues, municipal sewage sludge, food waste and used vegetable oil entering the digester

***Flow of total mass of substrate entering the digester***

**Eq. 4.8.1‑10**

where

*Fflow\_substrate,cr* Flow rate of crop residues, municipal sewage sludge, food waste or used vegetable oil entering the digester (kg day-1)

*Fflow\_substrate,cr,i* Flow rate of crop residue, municipal sewage sludge, food waste or used vegetable oil *i* entering the digester (kg day-1)

***Flow of TS entering the digester***

**Eq. 4.8.1‑11**

where

*TSflow\_substrate,cr* Flow rate of total solids in crop residues, municipal sewage sludge, food waste or used vegetable oil entering the digester (kg day-1)

*TSsubstrate,cr,I* Total solids concentration of crop residue, municipal sewage sludge, food waste or used vegetable oil *i* (kg t-1) (**Table 46**)

***Flow of VS entering the digester***

**Eq. 4.8.1‑12**

where

*VSflow\_substrate,cr* Flow rate of VS in crop residues, municipal sewage sludge, food waste or used vegetable oil entering the digester (kg day-1)

*TSflow,substrate,cr,i* Flow rate of TS in crop residue, municipal sewage sludge, food waste or used vegetable oil *i* entering the digester (kg day-1)

*VSsubstrate,cr,i* VS concentration of crop residue, municipal sewage sludge, food waste or used vegetable oil *i* (% TS) (**Table 46**)

***Flow of total N entering the digester***

**Eq. 4.8.1‑13**

where

*Nflow\_substrate,cr* Flow rate of total N in crop residues, municipal sewage sludge, food waste or used vegetable oil entering the digester (kg day-1)

*Nsubstrate,cr,i* N concentration of crop residue, municipal sewage sludge, food waste or used vegetable oil *i* (kg t-1) (**Table 46**)

***Flow of total C entering the digester***

**Eq. 4.8.1‑14**

where

*Cflow\_substrate,cr* Flow rate of total C in crop residues, municipal sewage sludge, food waste or used vegetable oil entering the digester (kg day-1)

*Csubstrate,cr,i* C concentration of crop residues, municipal sewage sludge, food waste or used vegetable oil *i* (kg kg-1). A default value of 0.45 kg kg-1 is used for all crop residues; default values of 0.091 kg kg-1 (for ‘fresh’ sludge on a wet basis, average of values from Odirile et al. (2021) for primary clarifier and microsieve treatments and from Serbanescu et al. (2017))[[12]](#footnote-13), 0.12 kg kg-1 (wet basis, Esteves and Devlin (2010) – cited in Slorach et al. (2019))[[13]](#footnote-14); and 0.0001 kg kg-1 (based on initial C concentration of 0.01% (w/v %) for raw linseed oil, stand linseed oil and olive oil (van Nieuwenhuijzen et al., 2019)) are used for municipal sewage sludge, food waste and used vegetable oil, respectively

#### For livestock manure stored for a period of time prior to entering the digester

***Flow of total mass of substrate entering the digester from liquid and solid manure storage systems***

**Eq. 4.8.1‑15**

where

*Fflow\_substrate,sm* Flow rate of fresh manure entering the digester from a liquid or solid manure storage system (kg or L day-1)

*Fflow\_substrate,sm,i* Flow rate of stored manure type *i* entering the digester (kg or L day-1), by animal group and manure management system

**Eq. 4.8.1‑16**

where

*Volumelandmanure,sm,i* Total volume of manure available for land application or addition to digester on a given day (1000 kg wet weight for solid manure and 1000 litres for liquid manure – **please note:** this is converted to a kg or L basis in the model code for use in this equation), by animal group and manure management system, calculated using **Eq. 4.5.3‑2**

*ManureADproportion,sm,i* Proportion of total manure available in storage added to the AD system, calculated as: Daily percentage of manure added (%, user-defined) / 100, by animal group and manure management system

***Flow of TS entering the digester***

**Please note:** for all manure substrate types (fresh and stored) entering the digester, it is not necessary to estimate the TS flow as this is not used in any subsequent equations. Therefore, in **Table 46**, the TS value for all manure types is zero.

**Eq. 4.8.1‑17**

where

*TSflow\_substrate,sm* Flow rate of total solids in substrate entering the digester from stored liquid or solid manure (kg day-1)

*TSsubstrate,sm,i* Total solids concentration of substrate *i* (kg t-1) (**Table 46**)

***Flow of VS entering the digester from liquid manure storage systems (dairy cattle)***

When the manure entering the digester has been stored for a period of time prior to being added to the system, the biomethane potential of this manure decreases significantly. This is accounted for by considering the VS consumed during the pre-digester storage period.

**Eq. 4.8.1‑18**

where

*VSflow\_substrate,slm,i* Flow rate of VS in stored liquid manure entering the digester (kg day-1), by animal group and manure management system

*∑VSloaded,slm,i* Sum of VS (kg) entering the manure storage system across all days of the pre-digester storage period; daily *VSloaded* for liquid manure is calculated using **Eq. 4.1.3‑4**, by animal group and manure management system

*∑VSconsumed,slm,i* Sum of VS (kg) consumed across all days of the pre-digester storage period; daily *VSconsumed* for liquid manure is calculated using **Eq. 4.1.3‑7**, by animal group and manure management system

***Flow of VS entering the digester from solid manure storage systems***

For solid manure systems, Holos assumes a fixed reduction in the amount of VS entering the system depending on the pre-AD storage method, to account for VS consumed during the pre-digester storage stage; *khydr,i* (the kinetic rate of degradation of manure) also significantly declines with manure age and storage duration, and is reduced accordingly (**Eq. 4.8.2‑3**).

**Eq. 4.8.1‑19**

where

*VSflow\_substrate,ssm,i* Flow rate of VS in stored solid manure entering the digester from previously stored solid manure (kg day-1), by animal group and manure management system

*Vssm,i* VS excreted (kg head-1 day-1), calculated using **Eq. 4.1.2‑1** for beef and dairy cattle

*VSreductionfactor,ssm,i* Fixed reduction in VS in stored solid manure entering the digester following a pre-digester storage period (**Table 45**). This reduction depends on the storage method and is applied to all animal groups

*#animals* Number of animals, by animal group

*ManureADproportion,ssm,i* Proportion of total manure available in storage added to the AD system, calculated as: Daily percentage of manure added (%, user-defined) / 100, by animal group and manure management system

***Flow of total N entering the digester***

The flow of total N into the digester in stored liquid or solid manure is calculated as the total amount of N excreted by the livestock plus N in bedding minus N losses via direct N2O emissions during the housing stage and indirect N2O losses via NH3 volatilisation and leaching during storage, i.e., *Nlandmanure*. This is then adjusted by the proportion of stored manure added to the digester.

**Eq. 4.8.1‑20**

where

*Nflow\_substrate,sm,i* Flow rate of total N in stored manure (liquid or solid) entering the digester (kg day-1), by animal group and manure management system

*Nlandmanure,sm,i* Daily manure N available in stored liquid or solid livestock manure for addition to the digester (kg N day-1), by animal group and manure management system, calculated using **Eq. 4.5.2‑6** for beef cattle and dairy cattle

***Flow of organic N entering the digester***

**For beef and dairy cattle:**

For beef and dairy cattle (including calves), the amount of organic N entering the digester in stored manure (*OrganicNlandmanure*) is calculated as the amount of organic N excreted minus housing and storage losses, using **Eq. 4.5.2‑4**. This is then adjusted by the proportion of stored manure added to the digester.

**Eq. 4.8.1‑21**

where

*OrganicNflow,substrate,sm,i* Flow rate of organic N in stored beef or dairy cattle manure (liquid or solid) entering the digester (kg day-1), by animal group and manure management system

*OrganicNlandmanure,sm,i* Daily organic N in stored beef or dairy cattle manure (liquid or solid) available for addition to the digestor (kg N day-1), by animal group and manure management system, calculated using **Eq. 4.5.2‑4**

**~~For broilers, layers and turkeys:~~**

~~For broilers, layers and turkeys, the amount of ON remaining in manure following the pre-AD storage stage is estimated as the difference between the total N and the TAN entering the digester in stored manure.~~

**~~Eq. 4.8.1‑22~~**

~~where~~

*~~OrganicN~~~~flow,substrate,sm~~* ~~Flow rate of organic N in stored solid poultry manure entering the digester (kg day~~~~-1~~~~)~~

*~~N~~~~flow,substrate,sm~~*~~Flow rate of total N in stored solid poultry manure entering the digester (kg day~~~~-1~~~~), calculated using~~ **~~Eq. 4.8.1‑20~~**

*~~TAN~~~~flow,substrate,sm~~* ~~Flow rate of organic N in stored solid poultry manure entering the digester (kg day~~~~-1~~~~), calculated using~~ **~~Eq. 4.8.1‑24~~**

***Flow of TAN entering the digester***

**For beef and dairy cattle:**

For beef and dairy cattle (including calves), the amount of TAN entering the digester in stored manure (*TANflow,substrate,sm*) is calculated as the amount of TAN excreted minus housing and storage NH3-N losses, using **Eq. 4.5.2‑1**. This is then adjusted by the proportion of stored manure added to the digester:

**Eq. 4.8.1‑23**

where

*TANflow,substrate,sm,i* Flow rate of TAN in stored beef or dairy cattle manure (liquid or solid) entering the digester (kg day-1), by animal group and manure management system

*TANlandmanure,sm,i* Daily organic N in stored beef or dairy cattle manure (liquid or solid) available for addition to the digestor (kg N), by animal group and manure management system, calculated using **Eq. 4.5.2‑1**

**~~For broilers, layers and turkeys:~~**

~~For broilers, layers and turkeys, the amount of TAN entering the digester is calculated based on the amount of TAN excreted by each of these groups, minus housing and storage NH~~~~3~~~~-N losses.~~

**~~Eq. 4.8.1‑24~~**

~~where~~

*~~TAN~~~~flow\_substrate,sm,i~~*~~Flow rate of TAN in stored solid manure entering the digester (kg day~~~~-1~~~~) for broilers, layers and turkeys, by animal group and manure management system~~

*~~TAN~~~~landmanure,sm,i~~*~~Daily organic N in stored solid poultry manure available for addition to the digestor (kg N), by animal group and manure management system, calculated using~~ **~~Eq. 4.5.2‑11~~**

***Flow of total C entering the digester***

**Eq. 4.8.1‑25**

where

*Cflow\_substrate,sm,i* Flow rate of total C in stored manure (liquid or solid) entering the digester (kg day-1), by animal group and manure management system

*Cstorage,sm,i* Amount of C available in stored manure (kg C day-1) by animal group and manure management system, calculated using **Eq. 4.1.3‑15**

### Methane and biogas potential through anaerobic digestion

The methane and biogas potential of the substrates are calculated based on the biodegradable fraction of the VS, the maximum BMP value, the hydrolysis rate and the hydraulic retention time (HRT). It should be remarked that these parameters can vary very significantly depending on the chemical composition of the product under consideration. Although default values from literature are provided, it is highly recommended to perform a laboratory biomethane potential test for each specific substrate under consideration in order to allow for accurate, case-specific simulations.

#### Flow of biodegradable volatile solids and methane potential

The methane potential of the substrate added to the anaerobic digester is based on the hydraulic retention time (HRT) and the kinetic hydrolysis rate (Tait et al., 2008). The kinetic rate of degradation of manure (*khydr*) also significantly reduces with the age of the manure, and is equal to 0.06 and 0.05 day-1 for manure dried in pads and stockpiled manure, respectively.

**Eq. 4.8.2‑1**

where

*VSflow\_biodeg* Flow rate of biodegradable VS (kg day-1)

*VSflow\_substrate,i* Total amount of VS in substrate *i* entering the digester (kg day-1)

*fbiodeg,VS,substrate,i* Biodegradable fraction of VS for substrate *i*. See box below for default values

Holos V4 will use the following default valuesfor *fbiodegrad,VS,substrate,i*:

*Dairy manure* 0.4 (Wilkie, 2005)

*Swine manure* 0.7 (Tait et al., 2008)

*Other manure* 0.55

*Green waste (leaves, branches, grass, straw)* 0.23 (Tait et al., 2008)

**Eq. 4.8.2‑2**

where

*CH4prod,total* Total CH4 production (Nm3 day-1), where Nm3 are normal metres cubed

*VSflow,degraded,i* Flow rate of degraded VS in substrate *i* during digestion (kg day-1), calculated using **Eq. 4.8.2‑3**

*BMPi* Theoretical biomethane potential of substrate *i* (Nm3 kg VS-1) (**Table 46**)

**Eq. 4.8.2‑3**

where

*VSflow,degraded,i* Flow rate of degraded VS during digestion in substrate *i* (kg day-1)

*VSflow,biodeg,i* Flow rate of biodegradable VS in substrate *i* (kg day-1)

*khydr,i* Hydrolysis rate of substrate *i* during digestion (day-1); see box below for default values

*HRT* Hydraulic retention time (days)

**Eq. 4.8.2‑4**

where

*VSflow,degraded* Flow rate of degraded VS during digestion (kg day-1)

Holos V4 will use the following default values for *khydr,i* and *HRT*:

khydr,i 0.18 day-1 for (fresh) manure, 0.13 day-1 for green wastes (Tait et al., 2008); 0.06 day-1 for manure dried in pads and 0.05 day-1 for stockpiled manure (Gopalan et al., 2013)

*HRT* 25 (1 reactor) or 60 days (2 reactors)

#### Biogas production

**Eq. 4.8.2‑5**

where

*Biogasprod,i* Biogas production of substrate *i* (Nm3 day-1)

*CH4prod,i* Methane production of substrate *i* (Nm3 day-1)

*fCH4,i* Fraction of methane in the biogas for substrate *i* (**Table 46**)

**Eq. 4.8.2‑6**

where

*Biogasprod,total* Total biogas production upon co-digestion of multiple substrates (Nm3 day-1)

#### Carbon dioxide production

#### Any biogas that is not converted into CH4 is transformed into CO2. The production of NH3, H2S and other trace compounds are not considered.

**Eq. 4.8.2‑7**

where

*CO2prod,i* CO2 production from substrate *i* (Nm3 day-1)

**Eq. 4.8.2‑8**

where

*CO2prod,total* Total CO2 production upon co-digestion of multiple substrates (Nm3 day-1)

#### Reactor dimensioning

The user can either specify the hydraulic retention time (HRT) or the available reactor volume. Typically, the HRT will be selected based on available prior knowledge regarding the substrate(s) to be treated and taking into account the organic loading rate (proposed upper limit at 3.5 kg VS m-3 d-1 and average of 1.6 (Bareha et al., 2021)). Hydraulic retention times for animal manures in a completely stirred tank reactor at mesophilic temperature typically range between 20 and 30 days (Hamilton, 2017; Wilkie, 2005), and a default HRT of 25 days in a single reactor is assumed for livestock manure. When crop residues are also added to the digester, Holos assumes a HRT of 60 days using two reactors in series, which is beneficial to reduce digestate storage emissions (Maldaner et al., 2018).

**Eq. 4.8.2‑9**

where

*Volumereactor* Reactor volume (m3), where 1,000 kg or 1,000 L is equal to 1 m3

*HRT* Hydraulic retention time (days)

*Fflow,substrate* Total flow rate of substrate entering the digester (m3 day-1), where *Fflow,substrate* is estimated using **Eq. 4.8.1‑1**, **Eq. 4.8.1‑10** and **Eq. 4.8.1‑15** for fresh manure, crop residues and stored manure, respectively

*1000* Conversion factor from kg/L to m3

**Eq. 4.8.2‑10**

where

*OLR* Organic loading rate (kg VS m-3 d-1) (upper limit: 3.5, average: 1.6 (Bareha et al., 2021))

*VSflow,substrate* Total flow rate of VS entering the digester (kg day-1), calculated based on **Eq. 4.8.1‑4**, **Eq. 4.8.1‑12**, **Eq. 4.8.1‑18** and **Eq. 4.8.1‑19** for fresh manure, crop residues, stored liquid manure and stored solid manure, respectively

*1000* Conversion factor from kg/L to m3

#### Valorization of methane

***Recoverable CH4 considering fugitive CH4 losses***

**Eq. 4.8.2‑11**

where

*CH4recover* Recoverable CH4 (Nm3 day-1)

*CH4prod,total* Total CH4 production (Nm3 day-1)

*FCH4,loss* Fraction of fugitive methane losses through digester equipment; default value of 0.03 is used (Flesch et al., 2011; Liebetrau et al., 2017; Walling and Vaneeckhaute, 2020)

***Total primary energy production potential***

**Eq. 4.8.2‑12**

where

*Energyprod* Total primary energy production (kWh day-1)

*CVCH4* Calorific value of CH4 (MJ Nm-3); default value of 35.17 is used

*Eenergy*Conversion coefficient kWh to MJ (MJ kWh-1); default value of 3.6 is used

***Electricity and heat production through a combined heat and power (CHP) system***

Using a combined heat and power system (CHP), the electrical efficiency is typically 40%, 50% of energy is transformed into heat and 10% is lost (EMU, 2021).

**Eq. 4.8.2‑13**

where

*Electricityprod,CHP* Total electricity production through CHP (kWh day-1)

*felectricity,CHP* Fraction of primary energy converted to electricity through CHP. A default value of 0.4 is used

**Eq. 4.8.2‑14**

where

*Heatprod,CHP* Total heat production through CHP (kWh day-1)

*fheat,CHP* Fraction of primary energy converted to heat through CHP. A default value of 0.5 is used

***Direct injection into the gas grid***

Prior to injection into the gas grid, biogas upgrading is required. Depending on the separation and purification methods used, additional methane losses may arise.

**Eq. 4.8.2‑15**

where

*CH4grid* Potential CH4 injection to the gas grid (kWh day-1)

*fCH4,loss,upgrading* Fraction of methane lost in upgrading plants. A default value of 0.0081 is used (Kvist and Aryal, 2019)

### Production of digestate and its composition

***Flow of total mass of digestate***

The total mass flow rate of digestate is equal to the sum of the mass flow rates of the substrates for co-digestion (PSU, 2012).

**Eq. 4.8.3‑1**

where

*Fflow.digestate* Flow rate of total mass of digestate (kg day-1)

*Fflow.substrate,i* Flow rate of substrate *i* entering the digester (kg day-1)

***Flow of TS in digestate***

**Eq. 4.8.3‑2**

where

*TSflow.digestate* Flow rate of TS in digestate (kg day-1)

*TSflow.substrate* Flow rate of TS in substrate entering the digester (kg day-1)

*VSflow,degraded* Flow rate of VS degraded during digestion (kg day-1)

***Flow of VS in digestate***

**Eq. 4.8.3‑3**

where

*VSflow.digestate* Flow rate of VS in digestate (kg day-1)

*VSflow.substrate* Flow rate of VS in substrate entering the digester (kg day-1)

*VSdegraded* Flow rate of VS degraded during digestion (kg day-1)

***Flow of total N in digestate***

It is considered that total N is conserved upon anaerobic digestion (volatilisation of NH3 to the biogas is neglected). Hence, the flow rate of total N in digestate is equal to the sum of the flow rates of N in the substrates for co-digestion.

**Eq. 4.8.3‑4**

where

*Nflow.digestate* Flow rate of total N in digestate (kg day-1)

*Nflow.substrate,i* Flow rate of total N in substrate *i* entering the digester (kg day-1)

***Flow of TAN in digestate***

**For beef and dairy cattle~~, and broilers, layers and turkeys~~:**

This is calculated based on the TAN available in substrate entering the digester and the TAN liberated through the degradation of VS.

**Eq. 4.8.3‑5**

where

*TANflow.digestate* Flow rate of TAN in digestate (kg day-1)

*TANflow.substrate,i* Flow rate of TAN in substrate *i* entering the digester (kg day-1)

*VSflow,degraded,i* Flow rate of VS in substrate *i* degraded during digestion (kg day-1)

*NVS,i* Total N content of VS in substrate *i* (kg N kg-1 VS)

**Eq. 4.8.3‑6**

where

*NVS,i* Total N content of VS in substrate *i* (kg N kg-1 VS)

*Nflow.substrate,i* Flow rate of total N in substrate *i* entering the digester (kg day-1)

***Flow of organic N in digestate***

**For beef and dairy cattle~~, and broilers, layers and turkeys~~:**

This is calculated based on total organic N available in the substrate entering the digester and the fraction mineralized through degradation of VS (mineralization of organic N).

**Eq. 4.8.3‑7**

where

*OrganicNflow.digestate* Flow rate of organic N in digestate (kg day-1)

*OrganicNflow.substrate,i* Flow rate of organic N in substrate *i* entering the digester (kg day-1)

*VSflow,degraded,i* Flow rate of VS in substrate *i* degraded during digestion (kg day-1)

*NVS,i* Total N content of VS in substrate *i* (kg N kg-1 VS)

***Flow of total C in digestate***

The flow of C in digestate is estimated based on the C fraction of the degraded VS - a default value of 0.55 is used (Cornell, 1996).

**Eq. 4.8.3‑8**

where

*Cflow.digestate* Flow rate of total C in digestate (kg day-1)

*Cflow.substrate,i* Flow rate of total C in substrate *i* entering the digester (kg day-1)

### Solid-liquid separation of digestate

Optionally, a liquid-solid separation can be performed as a digestate treatment, for example if the farmer is not able to apply the raw digestate to nearby fields. The mass and elemental distribution calculation is based on the separation efficiency of the equipment.

***Total mass flow rate of raw material in liquid fraction and solid fraction***

**Eq. 4.8.4‑1**

where

*Fflow,digestate,LF* Flow rate of liquid fraction of digestate (kg day-1)

*αflow* Separation coefficient: fraction of raw material in solid fraction following solid-liquid separation (**Table 47**)

*Fflow,digestate* Flow rate of total mass of digestate (kg day-1)

**Eq. 4.8.4‑2**

where

*Fdigestate,SF* Flow rate of solid fraction of digestate (kg day-1)

***Mass flow rate of TS in liquid fraction and solid fraction***

**Eq. 4.8.4‑3**

where

*TSflow,digestate,LF* Flow rate of TS in the liquid fraction of digestate (kg day-1)

αTS Separation coefficient: fraction of TS in the solid fraction following solid-liquid separation (**Table 47**)

**Eq. 4.8.4‑4**

where

*TSflow,digestate,SF* Flow rate of TS in the solid fraction of digestate (kg day-1)

***Mass flow rate of VS in liquid fraction and solid fraction***

**Eq. 4.8.4‑5**

where

*VSflow,digestate,LF* Flow rate of VS in the liquid fraction of digestate (kg day-1)

αVS Separation coefficient: fraction of VS in the solid fraction following solid-liquid separation (**Table 47**)

**Eq. 4.8.4‑6**

where

*VSflow,digestate,SF* Flow rate of VS in the solid fraction of digestate (kg day-1)

***Mass flow rate of total N in liquid fraction and solid fraction***

**Eq. 4.8.4‑7**

where

*Nflow,digestate,LF* Flow rate of total N in the liquid fraction of digestate (kg day-1)

*TANflow,digestate,LF* Flow rate of TAN in the liquid fraction of digestate (kg day-1), calculated using **Eq. 4.8.4‑9**

*OrganicNflow,digestate,LF* Flow rate of organic N in the liquid fraction of digestate (kg day-1), calculated using **Eq. 4.8.4‑11**

**Eq. 4.8.4‑8**

where

*Nflow,digestate,SF* Flow rate of total N in the solid fraction of digestate (kg day-1)

*TANflow,digestate,SF* Flow rate of TAN in the solid fraction of digestate (kg day-1), calculated using **Eq. 4.8.4‑10**

*OrganicNflow,digestate,SF* Flow rate of organic N in the solid fraction of digestate (kg day-1), calculated using **Eq. 4.8.4‑12**

***Mass flow rate of TAN in liquid fraction and solid fraction (for beef and dairy cattle, and broilers, layers and turkeys only)***

**Eq. 4.8.4‑9**

where

*TANflow,digestate,LF* Flow rate of TAN in the liquid fraction of digestate (kg day-1)

*αTAN*Separation coefficient: fraction of TAN in the solid fraction following solid-liquid separation (**Table 47**)

*TANflow,digestate* Flow rate of TAN in digestate (kg day-1)

**Eq. 4.8.4‑10**

where

*TANflow,digestate,SF* Flow rate of TAN in the solid fraction of digestate (kg day-1)

***Mass flow rate of organic N in liquid fraction and solid fraction (for beef and dairy cattle~~, and broilers, layers and turkeys~~)***

**Eq. 4.8.4‑11**

where

*OrganicNflow,digestate,LF* Flow rate of organic N in the liquid fraction of digestate (kg day-1)

*αOrgN*Separation coefficient: fraction of organic N in the solid fraction following solid-liquid separation (**Table 47**)

*OrganicNflow,digestate* Flow rate of organic N in digestate (kg day-1)

**Eq. 4.8.4‑12**

where

*OrganicNflow,digestate,SF* Flow rate of organic N in the solid fraction of digestate (kg day-1)

***Mass flow rate of total C in liquid fraction and solid fraction***

**Eq. 4.8.4‑13**

where

*Cflow,digestate,LF* Flow rate of total C in the liquid fraction of digestate (kg day-1)

*αC*Separation coefficient: fraction of total C in the solid fraction following solid-liquid separation (**Table 47**)

*OrganicNflow,digestate* Flow rate of total C in digestate (kg day-1)

**Eq. 4.8.4‑14**

where

*Cflow,digestate,SF* Flow rate of total C in the solid fraction of digestate (kg day-1)

### Storage of digestate

#### The following section presents C and N emissions that take place during the storage of raw (whole) digestate, liquid fraction and solid fraction of digestate. It must be remarked that the emission factors depend on the duration of storage as well as the storage conditions (e.g., covered or uncovered, temperature, volume). The estimation of daily emissions over time is carried out based on available literature on the topic.

***Methane emissions during storage of digestate (whole, liquid and solid fractions)***

**Eq. 4.8.5‑1**

where

*CH4store,digestate* CH4 emissions during digestate storage (kg day-1)

*ΥCH4,digestate* CH4 emission factor for digestate storage (g m-3 day-1) (see box below)

*Fflow,digestate* Storage volume of raw (whole) digestate entering storage on a daily basis) (m3), calculated using **Eq. 4.8.3‑1**)

Holos V4 will use the following equation to determine *ΥCH4,digestate*:

*ΥCH4,digestate*Υ = 0.0175\*(Mean daily temperature (°C))2 – 0.0245\*Mean daily temperature (°C) + 0.1433

This equation is based on a temperature-Υ relationship derived from best-case scenario values from Maldaner et al. (2018), where Υspring = 1.73 ± 0.53 g m-3 day-1 (12.8 °C); Υsummer = 5.80 ± 1.0 g m-3 day-1 (18.6 °C); Υfall = 3.15 ± 0.83 gm-3 day-1 (11.6 °C); Υwinter = 0.51 g m-3 day-1 (5.9 °C)

*ΥN2O,digestate*0.0652 g N2O m-3 day-1 (range 0.0004-0.13) (Vergote et al., 2020)

*ΥNH3,digestate*3.495 g NH3 m-3 day-1 is used (range 2.77-4.22) (Vergote et al., 2020)

***Nitrous oxide emissions during storage of digestate***

**Eq. 4.8.5‑2**

where

*N2Ostore,digestate* N2O emissions during digestate storage (kg day-1)

*ΥN2O,digestate* N2O emission factor for digestate storage (g m-3 day-1); see box above for default value

***Ammonia emissions during storage of digestate***

**Eq. 4.8.5‑3**

where

*NH3store,digestate* NH3 emissions during digestate storage (kg day-1)

*ΥNH3,digestate* NH3 emission factor for digestate storage (g m-3 day-1); see box above for default value

**Note:** Currently, in Holos V4, we do not have the necessary lookup values and coefficients to estimate *CH4store,digestate*, *N2Ostore,digestate* and *NH3store,digestate* for the solid and liquid fractions of separated digestate entering storage. Therefore, the model estimates these values only for whole digestate (i.e., digestate that has not undergone solid-liquid separation). Once the required values/coefficients become available, a future version of Holos may allow the calculation of storage emissions from the liquid and solid fractions of digestate.

### Fresh and stored digestate available for land application

#### Volume of digestate available for application to land from all livestock

***For fresh raw digestate (including liquid and solid fractions)***

For whole raw digestate and for raw digestate that has undergone liquid-solid separation and is applied directly from the AD system to land, the amount of digestate, N and C (for all animal groups), as well as ON and TAN (for beef and dairy cattle, and broilers, layers and turkeys only) available for application to land are equal to the flows of these from the digester, calculated as follows:

For whole (i.e., non-separated) raw digestate: total amount of digestate available for land application (Total\_Volumelanddigestate,raw) - **Eq. 4.8.3‑1** (Fflow,digestate); total N available for land application (Nlanddigestate,raw) – **Eq. 4.8.3‑4** (Nflow,digestate); total TAN available for land application (TANlanddigestate,raw) - **Eq. 4.8.3‑5** (TANflow,digestate); total organic N available for land application (OrganicNlanddigestate,raw) - **Eq. 4.8.3‑7** (OrganicNflow,digestate); total C available for land application (Clanddigestate,raw) – **Eq. 4.8.3‑8** (Cflow,digestate).

For raw digestate that has undergone liquid-solid separation, liquid fraction: total amount of digestate available for land application (Total\_Volumelanddigestate,raw,LF) – **Eq. 4.8.4‑1** (Fflow.digestate,LF); total N available for land application (Nlanddigestate,raw,LF) – **Eq. 4.8.4‑7** (Nflow,digestate,LF); total TAN available for land application (TANlanddigestate,raw,LF) – **Eq. 4.8.4‑9** (TANflow,digestate,LF); total organic N available for land application (OrganicNlanddigestate,raw,LF) – **Eq. 4.8.4‑11** (OrganicNflow-digestate,LF); total C available for land application (Clanddigestate,raw,LF) – **Eq. 4.8.4‑13** (Cflow,digestate,LF).

For raw digestate that has undergone liquid-solid separation, solid fraction: total amount of digestate available for land application (Total\_Volumelanddigestate,raw,SF) – **Eq. 4.8.4‑2** (Fflow.digestate,SF); total N available for land application (Nlanddigestate,raw,SF) –**Eq. 4.8.4‑8** (Nflow,digestate,SF); total TAN available for land application (TANlanddigestate,raw,SF) – **Eq. 4.8.4‑10** (TANflow,digestate,SF); total organic N available for land application (OrganicNlanddigestate,raw,SF) – **Eq. 4.8.4‑12** (OrganicNflow-digestate,SF); total C available for land application (Clanddigestate,raw,SF) – **Eq. 4.8.4‑14** (Cflow,digestate,SF).

***For stored digestate (including liquid and solid fractions)***

For digestate that is stored prior to application to land, the amount of whole digestate, liquid fraction and solid fraction available is equal to the amount entering storage, i.e., Total\_Volumelanddigestate,stored,raw = Total\_Volumelanddigestate,raw (calculated using **Eq. 4.8.3‑1** (Fflow,digestate)), Total\_Volumelanddigestate,stored,LF = Total\_Volumelanddigestate,LF (calculated using **Eq. 4.8.4‑1** (Fflow,digestate,LF)), and Total\_Volumelanddigestate,stored,SF = Total\_Volumelanddigestate,SF (calculated using **Eq. 4.8.4‑2** (Fflow,digestate,SF)).

For total N, TAN (for beef and dairy cattle, broilers, layers and turkeys), organic N (for beef and dairy cattle, broilers, layers and turkeys) and total C, losses occurring during storage must be accounted for and subtracted from the amounts contained in the digestate or digestate fraction entering storage.

***Total N available for land application in stored whole, liquid fraction and solid fraction digestate***

**Eq. 4.8.6‑1**

where

*Nlanddigestate,store* Total N available in stored digestate (whole, liquid fraction or solid fraction) for application to land (kg day-1)

*Nflow.digestate* Flow rate of total N in digestate (kg day-1), calculated using **Eq. 4.8.3‑4**

*N2Ostore,digestate* Nitrous oxide emissions during digestate storage (kg N2O-N day-1), calculated using **Eq. 4.8.5‑2**

*NH3store,digestate* Ammonia emissions during digestate storage (kg NH3-N day-1), calculated using **Eq. 4.8.5‑3**

***Total C available for land application in stored whole, liquid fraction and solid fraction digestate***

**Eq. 4.8.6‑2**

where

*Clanddigestate,store* Total C available in whole stored digestate (whole, liquid fraction or solid fraction) for application to land (kg day-1)

*Cflow.digestate* Flow rate of total C in digestate (kg day-1), calculated using **Eq. 4.8.3‑8**

*CH4store,digestate* Methane emissions during digestate storage (kg day-1), calculated using **Eq. 4.8.5‑1**

## Emissions from land application of raw and stored digestate

(by S.J. Pogue)

The application to land of whole (i.e., non-separated), liquid fraction or solid fraction raw or stored digestate results in further losses of N to the environment via direct N2O losses, indirect N2O losses via volatilization and leaching, NH3 and NO3 losses to ground and surface water bodies. The general approach used to estimate these N losses from land-applied digestate follows that used for land-applied manure (see **Section 4.6**).

### Direct N2O emissions from land-applied digestate

The estimation of direct N2O emissions from raw land-applied digestate (i.e., digestate that is applied directly to land once it exits the AD system) follows the same approach used for land-applied manure (**Section 4.6.1**), using the amounts of digestate N available for application to land: *Nlanddigestate,raw* (**Eq. 4.8.3‑4**), *Nlanddigestate,LF* (**Eq. 4.8.4‑7**) or *Nlanddigestate,SF* (**Eq. 4.8.4‑8**), for raw whole digestate, raw liquid fraction or raw solid fraction, respectively. For stored digestate, the same approach is used, but the emissions equations use *Nlanddigestate,store, Nlanddigestate,store,LF, Nlanddigestate,store,SF* (**Eq. 4.8.6‑1**), for the application of stored whole digestate, stored liquid fraction or stored solid fraction, respectively.

**To calculate N2O from digestate applied to a specific field:**

Direct N2O emissions from land-applied digestate (raw and stored, whole, liquid and solid fractions) are estimated for field *n* (*N2O-Ndigestatedirect\_\_\_\_\_(t,field n)*) based on the specified digestate application rate for the field, specific to the type of digestate applied to field *n* in year *t*. Direct N2O emissions from these field-specific applications are then calculated using the same approach as for field-applied manure (see **Eq. 4.6.1‑1**).

***Any digestate not applied to a specific field (‘leftover’ digestate) is considered a further source of direct N2O emissions. For this* purpose*, it is assumed that, as for manure, the ‘leftover’ digestate is spread equally across the farm’s fields (excl. native rangeland, if present),* meaning that the emission factor is averaged across all available fields (excl. native rangeland), weighted by their area (see Eq. 4.6.1‑3 and Eq. 4.6.1‑5 - Eq. 4.6.1‑6).** As for leftover manure, leftover digestate N is calculated as the difference between the total amount of digestate N available for land application minus all field-specific applications, i.e., *Nlanddigestateremaining(t) = ∑allscenarioNlanddigestate\_\_\_\_\_ - ∑allscenarioNlanddigestate\_\_\_\_\_(t,field n)*) (see **Eq. 4.6.1‑4**).

Total direct N2O emissions from land-applied digestate are estimates as the sum of emissions from all field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

### Indirect N2O emissions from land-applied digestate

#### Ammonia emissions from land-applied digestate

Ammonia emissions during the land application of digestate (raw and stored, whole, liquid fraction or solid fraction) are estimated using the same general approach used for land-applied manure from swine, sheep and other livestock (see **Section 4.6.2.3**). For all types of land-applied digestate, a single *Fracvolatilization\_landapplication* value of 0.1705 kg NH3-N (kg N)-1 is used, calculated as the average of all provincial *Fracvolatilization\_landapplication* values for dairy cattle and swine manure for the year 2020 (the most recent year reported in ECCC (2022), see **Table 61** and **Table 62**). An average dairy/swine manure value was used as, based on expert opinion, the characteristics of digestate are typically closest to those of liquid dairy/swine manure.

**To calculate NH3 emissions from digestate applied to a specific field:**

Ammonia emissions from digestate application to field *n* in year *t* (*NH3\_Ndigestate\_\_\_\_\_(t,field n)*) are estimated as the product of the amount of digestate N applied (*Nlanddigestate\_\_\_\_\_(t,field n)*) and the *Fracvolatilization\_landapplication* value (see **Eq. 4.6.2‑12**).

***Any digestate not applied to a specific field (‘leftover’ digestate) is considered a source of further NH3 emissions. For this purpose, it is assumed that the ‘leftover’ digestate N is spread equally across the farm’s fields (excl. native rangeland, if present),* with NH3 emissions estimated using the same *Fracvolatilization\_landapplication* value of 0.1705 kg NH3-N (kg N)-1.** Emissions from the application of leftover digestate are estimated on a per field basis using the same approach employed for manure application for sheep, swine and other livestock. Ammonia emissions from the application of leftover digestate on the farm’s fields are calculated based on the amount of leftover digestate (*Nlanddigestateremaining(t)*) and *Fracvolatilization\_landapplication* (see  **Eq. 4.6.2‑15** - **Eq. 4.6.2‑16**).

Total NH3 emissions from the land application of digestate to field *n* in year *t* (*NH3\_Nalldigestate(t,field n)*) are estimated as the sum of emissions from field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

**Ammonia emissions from the land application of digestate are calculated on a daily basis.**

### Nitrous oxide volatilization from digestate following land application

Indirect N2O-N emissions via volatilization (*N2O-Ndigestatevolatilization\_\_\_\_\_(t,field n)*) are estimated using the same approach used for land-applied manure, i.e., as the product of NH3-N emissions from field-specific or leftover digestate application to field *n* in year *t* and the volatilization EF (**Table 36**) – see **Eq. 4.6.3‑1 - Eq. 4.6.3‑2**.

Total indirect N2O emissions via volatilization from the land application of digestate to field *n* in year *t* (*N2O\_Nalldigestatevolatilization(t,field n)*) are estimated as the sum of emissions from field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

**Indirect N2O emissions from the land application of digestate are calculated on a daily basis.**

#### Adjustment of NH3 volatilization estimates from land application of digestate following indirect N2O emissions

As for NH3 emissions from manure following land application, the NH3 emissions following application of digestate need to be adjusted to avoid double-counting of subsequent indirect N2O-N losses. This is achieved using the same approach, i.e., *NH3\_Ndigestate\_\_\_\_\_\_adju* is equal to NH3-N emissions minus N2O-N emissions for both field-specific and leftover digestate applications (see **Eq. 4.6.3‑5** - **Eq. 4.6.3‑6**).

Total adjusted NH3 emissions from the land application of digestate to field *n* in year *t* (*NH3\_Nalldigestate\_adju(t,field n)*) are estimated as the sum of emissions from field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

**Adjusted NH3 emissions from land application of digestate are calculated on a daily basis.**

### Indirect N losses from land-applied digestate via leaching and runoff

As for N2O-N leaching losses from manure following land application, emissions following digestate application (*N2O-Ndigestateleach\_\_\_\_\_(t,field n)*) are estimated as the product of the amount of digestate N added to the field (*Nlanddigestate\_\_\_\_\_(t,field n*) for field-specific applications and *Nlanddigestateremaining(t,field n)* for leftover digestate), the leaching fraction (*Fracleach*) and the leaching EF (*EFleach*) – see **Eq. 4.6.4‑1** - **Eq. 4.6.4‑2**, where *Fracleach* is calculated using **Eq. 2.6.6‑1** and *EFleach* = 0.011 (IPCC, 2019).

Total indirect N2O emissions via leaching/runoff from the land application of digestate to field *n* in year *t* (*N2O-Nalldigestateleach(t,field n)*) are estimated as the sum of emissions from field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

**To calculate the actual amount of N leached:**

To calculate the actual amount of N leached as NO3-N (*NO3-Ndigestateleach\_\_\_\_\_(t,field n)*), again the approach for land-applied manure is used, where NO3-N losses from field *n* in year *t* following digestate application are estimated as the product of the amount of digestate N added to the field (*Nlanddigestate\_\_\_\_\_(t,field n*) for field-specific applications and *Nlanddigestateremaining(t,field n)* for leftover digestate) and the leaching fraction (*Fracleach*) – see **Eq. 4.6.4‑6** - **Eq. 4.6.4‑7**.

Total NO3-N losses via leaching/runoff from the land application of digestate to field *n* in year *t* (*NO3-Nalldigestateleach(t,field n)*) are estimated as the sum of emissions from field-specific and leftover digestate applications, and total emissions at the farm scale are the sum of emissions from all fields.

### Total indirect N2O emissions from land-applied digestate

**Eq. 4.9.5‑1**

where

*N2Odigestatemanure* Total indirect N2O emissions from digestate applied to land (kg N2O-N)

### Total N2O emissions from land-applied digestate

**Eq. 4.9.6‑1**

where

*N2O-Ndigestatesoils* Total direct and indirect N2O-N emissions from digestate applied to land (kg N2O-N)

### Digestate **C and N for the** ICBM/IPCC Tier 2 and soil N2O models

This section describes the calculations used to estimate the amount of C and N added to the soil C and N pools following land-spreading, as well as the amount of water available in land-applied digestate. The amount of C entering the soil C pool serves as input to the IPCC Tier 2 and ICBM soil C models in Holos and the amount of N added to the soil N pool serves as input to the model (adapted from Liang et al. 2020) used for the multi-year estimation of soil N2O emissions. The amount of C and N added to the relevant soil pools account for any land application losses.

#### Carbon

To estimate digestate C applied to soil in field *n*:

**Eq. 4.9.7‑1**

where

*Cmodel\_digestatetype(t,field n)* Amount of C added to the soil in digestate (kg C) applied to field *n* in year *t*, by digestate type

*fdigestatetype(t,field n)* Fraction of digestate available for land application that is applied to field *n* in year *t*. This is applied to tilled or untilled land during the specified day of application (dimensionless), and is specific to the type of digestate applied and the field. *fdigestatetype(t,field n)* is calculated as: *Volumedigestateremoved / (Total\_Volumelanddigestate*), where: *Volumedigestateremoved* = volume of digestate applied to field *n* on the day of removal (kg), by digestate type, calculated as: digestate application rate (kg ha-1, specified by user) \* area of land receiving digestate (ha, specified by user); *Total\_Volumelanddigestate*= amount of digestate available on the day of removal (prior to removal)

*Clanddigestatetype(t)* Total amount of C available in digestate (kg C), by digestate type

**Eq. 4.9.7‑2**

where

*Cmodel\_digestate(t,field n)* Total amount of C added to the soil C pool (kg C) in digestate, specific to field *n* in year *t*

***Any digestate not applied to a specific field (‘leftover’ digestate) is spread equally across all of the farm’s fields (excl. native rangeland, if present)*.**

**Eq. 4.9.7‑3**

where

*Cmodel\_landmanureremaining(t)* Remaining digestate C available for addition to the soil C pool minus digestate C applied to specific fields (kg C) in year *t*

*Clanddigestate(t)* Total amount of C available in all types of digestate (kg C, raw and stored, whole, liquid and solid fractions) in year *t*

*Cmodel\_digestate,allfields(t)* Total amount of C in digestate (kg C) applied to specific fields in year *t*

**Eq. 4.9.7‑4**

where

*Cmodel\_digestateremaining(t,field n)* Remaining digestate C added to the soil C pool (kg C), specific to field *n* in year *t*

**Eq. 4.9.7‑5**

where

*Total\_Cmodel\_digestate(t,field n)* Total amount of C added to the soil C pool (kg C) in all field-applied digestate, specific to field *n* in year *t*

#### Nitrogen

Digestate N applied to soil (after all land application N losses) in field *n* is estimated using the same approach used for manure N applied to soil (after all land application losses). For field *n*, the total amount of digestate N added to the soil N pool (*Total\_Nmodel\_digestate(t,field n)*) is estimated as the total amount of digestate N applied (before land application losses) in all field-specific and leftover applications (i.e., the sum of all *Nlanddigestate\_\_\_\_\_(t,field n)* and *Nlanddigestateremaining\_\_\_\_\_(t,field n)* estimates) minus all direct and indirect N losses (i.e., the sum of all *N2O-Ndigestatedirect\_\_\_\_\_(t,field n)*, *NH3\_Ndigestate\_\_\_\_\_(t,field n)*, *N2O-Ndigestateleach\_\_\_\_\_(t,field n)* and *NO3-Ndigestateleach\_\_\_\_\_(t,field n)* estimates) (see **Eq. 4.7.2‑1** for general approach).

## Conversions

**Eq. 4.9.7‑1**

**Eq. 4.9.7‑2**

**Eq. 4.9.7‑3**

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**Table 6**

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**Table 18**

See **Section 3.6** for references

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# Animals in grazing situations

(by S.J. Pogue and A.W. Alemu)

## Enteric CH4 emissions from grazing animals on pasture

For livestock grazing on pasture (incl. young), enteric CH4 emissions are estimated using the same approach as for non-grazing animals – see **Sections 3.1** (beef cattle), **3.2** (dairy cattle), **3.3** (sheep) and **3.4** (other livestock).

## Manure carbon and CH4 emissions from livestock manure deposited on pasture

In Canada, between 16% (for dairy cattle) and 72% (for llamas and alpacas) of manure produced by grazing livestock is managed in pasture, range or paddock systems (**Table 29**), where faeces and urine are deposited directly in the field. Carbon utilization by animals on pasture is a function of the C content of pasture forage and its digestibility. The entire undigested C content (e.g., 39% for beef cattle, Baron et al., 2002) is assumed to be returned to the field and distributed throughout the field by the animal. The amount of C excreted varies among animal groups and can range between 25 and 60% (<http://www.soilcc.ca/resources.htm>). The ungrazed portion of the biomass (**Section 2.1.2.6**) and the amount of excreted C minus CH4 losses from manure deposited on pasture will be used as an input to the IPCC Tier 2 and ICBM soil C models, for grazed pastures. The amount of N excreted minus direct and indirect N losses will be used as manure inputs to the soil N pool for the soil N2O models, for grazed pastures.

### Manure carbon deposited on pasture

For livestock on pasture, only faecal C is added to the field (no bedding C). The amount of C excreted by grazing animals (*Cexcretion*) is estimated using the same approach as for non-grazing livestock – to estimate faecal C excretion for each animal group, see **Section 4.1.1.1**.

### CH4 emissions from manure deposited on pasture for all animal groups

To estimate CH4 emissions from manure deposited on pasture (*CH4pasture*), we use the same approach as for solid manure excreted by non-grazing animals – see **Section 4.1.2**.   
**Note:** in **Eq. 4.1.2‑4**, Bo (maximum CH4 producing capacity, m3 CH4 kg-1 VS) should be set to 0.19 for all livestock on pasture.

## **Direct N2O emissions from livestock manure deposited on pasture**

### Direct N2O emissions from livestock manure deposited on pasture

Direct daily N2O emissions occur from livestock manure (urine + faeces) deposited on pasture via combined nitrification and denitrification of N contained in the manure. The direct N2O emission rate (kg N2O head-1 day-1) depends on the amount of N excreted by the animal and default N2O emission factors (*EFdirect*) from ECCC (2022) for animals on pasture/range/paddock (**Table 36**). For grazing livestock in BC, AB, SK and MB, the direct N2O EF is the same for all soil texture classes and is based on a study for beef cattle in Western Canada (Lemke et al., 2012). For grazing livestock in ON, QC and the Atlantic provinces, the direct N2O EFs depend on the soil texture class and are based on a dairy cow study in Eastern Canada (Rochette et al., 2014). The EF is applied to the amount of N excreted by the animal (*Nexcretion*), assuming that 75% of this is contained in urine (Rochette et al., 2014). For Western Canada, an EF of 0.00043 kg N2O-N kg-1N is applied for all soil texture classes (the EF for urine is 0.0006 and the EF for dung is 0), while in Eastern Canada a different EF is applied for each soil texture class: 0.0078 kg N2O-N kg-1 N for fine-textured soil, 0.0062 kg N2O-N kg-1 N for medium-textured soil and 0.0047 kg N2O-N kg-1 N for coarse-textured soil (Rochette et al., 2014).

**For beef cattle, dairy cattle, broilers, layers and turkeys:**

**Eq. 5.3.1‑1**

where

*N2O-Ndirectpasture\_rate* Direct N2O-N emissions from manure deposited on pasture for beef cattle, dairy cattle, broilers, layers and turkeys (kg N2O-Nhead-1 day-1)

*Nexcretion\_rate* Daily N excretion by beef and dairy cattle,broilers, layers and turkeys

*EFdirect* Direct N2O-N emission factor for urine deposited on pasture (kg N2O-N kg-1 N) For Western Canada (BC, AB, SK, MB), an EF of 0.00043 kg N2O-N kg-1N for all soil texture classes; for Eastern Canada (ON, QC, Atlantic provinces) the EF is dependent on soil texture: 0.0078 kg N2O-N kg-1 N for fine-textured soil, 0.0062 kg N2O-N kg-1 N for medium-textured soil and 0.0047 kg N2O-N kg-1 N for coarse-textured soil (**Table 36**)

**For all other livestock:**

**Eq. 5.3.1‑2**

where

*N2O-Ndirectpasture\_rate* Direct N2O-N emissions from manure deposited directly on pasture for sheep, swine, poultry (except broilers, layers and turkeys), and other livestock (kg N2O-Nhead-1 day-1)

*Nexcretion\_rate* Daily N excretion (kg N head-1 day-1) for sheep (**Eq. 4.2.1‑18**), swine (**Eq. 4.2.1‑24**), pullets (**Eq. 4.2.1‑28**), other livestock (**Table 42**)

*EFdirect* Direct N2O-N emission factor for urine deposited on pasture (kg N2O-N kg-1 N) For Western Canada (BC, AB, SK, MB), an EF of 0.00043 kg N2O-N kg-1N for all soil texture classes; for Eastern Canada (ON, QC, Atlantic provinces) the EF is dependent on soil texture: 0.0078 kg N2O-N kg-1 N for fine-textured soil, 0.0062 kg N2O-N kg-1 N for medium-textured soil and 0.0047 kg N2O-N kg-1 N for coarse-textured soil (**Table 36**)

**For all livestock:**

**Eq. 5.3.1‑3**

where

*N2O-Ndirectpasture* Direct N2O-N emissions from dung and urine deposited directly on pasture (kg N2O-Nday-1), by animal group

**Eq. 5.3.1‑4**

where

*Total\_ N2O-Ndirectpasture* Total direct N2O-N emissions from manure for all animals managed on pasture (kg N2O-N), by livestock type

## Indirect N2O emissions from manure deposited on pasture for all livestock types

### Ammonia emissions from manure deposited on pasture for beef cattle and dairy cattle

#### Urinary nitrogen/total ammonical nitrogen (TAN) for beef and dairy cattle (including calves) on pasture

To calculate the amount of TAN excreted in urine by grazing beef and dairy animals on pasture, use **Eq. 4.3.1‑1** to **Eq. 4.3.1‑4**.

#### Faecal/Organic nitrogen for beef and dairy cattle on pasture

For grazing beef and dairy cattle, there is no application of bedding material and organic N is equal to the amount of N excreted through faeces. To calculate the amount of N excreted through faeces (faecal N) by grazing beef and dairy animals on pasture, use **Eq. 4.3.1‑5** and **Eq. 4.3.1‑6**.

#### Ammonia volatilization from manure deposited on pasture for beef and dairy cattle (including calves)

**Eq. 5.4.1‑1**

where

*ATApasture* Ambient temperature-based adjustments used to correct default NH3 EF (kg NH3-N kg-1 TAN, **Table 43**) for grazing pasture (enclosed, open range)

*T* Average outdoor daily temperature (°C)

**Eq. 5.4.1‑2**

where

*EFpasture-adju* Adjusted NH3 emission factor for grazing pasture (kg NH3-N kg-1 TAN) (0 ≤ EFpasture-adju ≤ 1)

*EFpasture* Default NH3 emission factor for pasture grazing (enclosed, open range, **Table 43**)

**Eq. 5.4.1‑3**

where

*NH3\_Npasture\_rate* NH3-N emissions from beef and dairy cattle manure deposited directly on pasture (kg NH3 head-1 day-1)

**Eq. 5.4.1‑4**

where

*NH3\_Npasture* NH3-N emissions from beef and dairy cattle manure deposited directly on pasture (kg NH3-N), by animal group

*#animals* Number of animals

**Eq. 5.4.1‑5**

where

*Total\_ NH3-Npasture* Total NH3-N emissions via volatilization from manure for all animals managed on pasture (kg NH3-N), by livestock type

**Ammonia emissions from grazing beef and dairy cattle on pasture are calculated on a daily basis.**

### Ammonia emissions from manure deposited on pasture for all non-cattle grazing livestock

#### Total N excretion for non-cattle livestock on pasture

The daily N excretion rate (kg N head-1 day-1) is calculated using **Eq. 4.2.1‑18** for sheep, **Eq. 4.2.1‑24** for swine, **Eq. 4.2.1‑28** for pullets, broilers and layers, and **Table 42** for allother livestock.

#### Ammonia volatilization from manure deposited on pasture for non-cattle animals

Ammonia emissions from manure deposited on pasture for all non-cattle grazing livestock are estimated using a default IPCC (2019) *Fracvolatilization* value of 0.21 (kg NH3–N + NOx–N) (kg N applied or deposited)–1 (**Table 36**).

**Eq. 5.4.2‑1**

where

*NH3\_Npasture\_rate* NH3 emissions from non-cattle manure deposited directly on pasture (kg NH3-N head-1 day-1), by animal group

*Fracvolatilization* Fraction of manure N volatilized as NH3 and NOx for manure deposited directly on pasture (**Table 36**)

**Eq. 5.4.2‑2**

where

*NH3\_Npasture* NH3 emissions from non-cattle manure deposited directly on pasture (kg NH3-N), by animal group

*#animals* Number of animals

**Eq. 5.4.2‑3**

where

*Total\_ NH3-Npasture* Total NH3-N emissions via volatilization from manure for all animals managed on pasture (kg NH3-N), by livestock type

### N2O volatilization from manure deposited on pasture for all livestock

For beef and dairy cattle, *Fracvolatilization* values for each animal group are calculated using **Eq. 5.3.5‑1**; for all other livestock types on pasture, default IPCC (2019) values are used (**Table 36**).

**For beef and dairy cattle (including beef and dairy calves):**

**Eq. 5.4.3‑1**

where

*Fracvolatlization* Fraction of manure N excreted that is volatilized as NH3 and NOx from beef and dairy cattle manure deposited on pasture (kg NH3-N kg-1 N)

*NH3-Npasture* NH3 emissions from beef and dairy cattle managed on pasture (kg NH3-N), by animal group

*Nexcretion* Total amount of N excreted by beef or dairy cattle on pasture (kg N day-1)

**For all animal groups:**

**Eq. 5.4.3‑2**

Derived from IPCC 2019, Eq. 10.26, Eq. 10.28

where

*N2O-Nvolatilizationpasture\_rate* Indirect N2O emissions via volatilization from manure deposited directly on pasture (kg N2O-N head-1 day-1)

*Fracvolatilization* Fraction of manure N excreted that is volatilized as NH3 and NOx from manure deposited directly on pasture (kg NH3-N kg-1 N); calculated using **Eq. 5.3.5‑1** for beef and dairy cattle and derived from **Table 36** for all other animal groups

*EFvolatilization* Emission factor for volatilization [kg N2O-N (kg NH3-N + NOx-N volatilized)-1] (**Table 36**)

**Eq. 5.4.3‑3**

where

*N2O-Nvolatilizationpasture* Indirect N2O emissions via volatilization from manure deposited directly on pasture (kg N2O-N), by animal group

*#animals* Number of animals

**Indirect N2O emissions are calculated on a daily basis for all animal groups.**

**Eq. 5.4.3‑4**

where

*Total\_ N2O-Nvolatilizationpasture* Total indirect N2O emissions via volatilization from manure for all animals managed on pasture (kg N2O-N), by livestock type

*N2O-Nvolatilizationpasture* Indirect N2O emissions via volatilization from manure deposited directly on pasture (kg N2O-N), by animal group

#### Adjustment of NH3 volatilization estimates from manure deposited on pasture following indirect N2O emissions

Ammonia emissions from manure deposited on pasture need to be adjusted to avoid double-counting of subsequent indirect N2O-N losses.

**For all animal groups:**

**Eq. 5.4.3‑5**

where

*NH3\_Npasture\_adju* Adjusted daily NH3-N emissions from manure deposited directly on pasture (kg NH3-N day-1),by animal group

**Eq. 5.4.3‑6**

where

*Total\_NH3\_Npasture\_adju* Adjusted daily NH3-N emissions from manure deposited directly on pasture (kg NH3-N day-1), by livestock type

**Adjusted ammonia emissions from manure deposited on pasture are calculated on a daily basis.**

### Indirect N losses from manure deposited on pasture via leaching and runoff

**For all animal groups:**

**Eq. 5.4.4‑1**

Derived from IPCC 2019

where

*N2O-Nleachingpasture\_rate*N2O emissions due to leaching and runoff from manure deposited directly on pasture (kg N2O-N head-1 day-1), by animal group

*Nexcretion\_rate* N excreted by livestock in manure deposited directly on pasture (kg N head-1 day-1)

*Fracleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* Emission factor for leaching [kg N2O-N (kg N)-1], see box below

**Eq. 5.4.4‑2**

where

*N2O-Nleachingpasture* IndirectN2O-N emissions via leaching and runoff from manure deposited directly on pasture (kg N2O-N day-1), by animal group

**Eq. 5.4.4‑3**

where

*Total\_N2O-Nleachingpasture* N2O-N leached from manure deposited directly on pasture (kg N2O-N), by livestock type

Holos V4 will use the following constant value:

*EFleach* 0.011 (IPCC 2019)

**To estimate the actual amount of NO3-N leached:**

**Eq. 5.4.4‑4**

where

*NO3-Nleachingpasture* NO3-N leached from manure deposited directly on pasture (kg NO3-N), by animal group

**Eq. 5.4.4‑5**

where

*Total\_NO3-Nleachingpasture* NO3-N leached from manure deposited directly on pasture (kg NO3-N), by livestock type

### Total indirect N2O emissions from manure

**For all animal groups:**

**Eq. 5.4.5‑1**

where

*N2Oindirectpasture* Total indirect N2O emissions from manure deposited on pasture (kg N2O-N day-1), by animal group

### Total N2O emissions from livestock manure deposited on pasture

**For all animal groups:**

**Eq. 5.4.6‑1**

where

*N2O-Npasture* Total direct and indirect manure N2O emissions from livestock manure deposited o pasture (kg N2O-N), by animal group

## Total emissions

Emissions from livestock manure deposited on pasture should be summed for all animal groups within each broad livestock type (i.e., beef cattle, dairy cattle, sheep, etc.).

### Manure CH4 emissions

**Eq. 5.5.1‑1**

where

*Total\_CH4pasture* Total CH4 emissions from manure deposited directly on pasture (kg CH4 year-1), by livestock type

*CH4manure* Manure CH4 emissions from manure deposited directly on pasture (kg CH4), by animal group

### Manure N emissions

**Eq. 5.5.2‑1**

where

*Total\_N2O-Ndirectpasture* Total direct N2O emissions from manure deposited directly on pasture (kg N2O-N year-1), by livestock type

*N2O-Ndirectpasture* Direct N2O emissions from manure deposited on pasture (kg N2O-N)

**Eq. 5.5.2‑2**

where

*Total\_NH3\_Npasture* Total NH3-N emissions from manure deposited directly on pasture (kg NH3-N), by livestock type

*NH3\_Npasture* Ammonia emissions from manure deposited on pasture (kg NH3-N), by animal group

**Eq. 5.5.2‑3**

where

*Total\_N2O-Nvolatilizationpasture* Total manure volatilization N emissions from manure deposited directly on pasture (kg N2O-N year-1), by livestock type

*N2O-Nvolatilizationpasture* Volatilization N emissions from manure deposited directly on pasture (kg N2O-N), by animal group

**Eq. 5.5.2‑4**

where

*Total\_N2O-Nleachingpasture* Total leaching N emissions from manure deposited directly on pasture (kg N2O-N year-1), by livestock type

*N2O-Nleachingpasture* Leaching N emissions from manure deposited directly on pasture (kg N2O-N), by animal group

**Eq. 5.5.2‑5**

where

*Total\_NO3-Nleachingpasture* Total leaching NO3-N emissions from manure deposited directly on pasture (kg NO3-N year-1), by livestock type

*NO3-Nleachingpasture* Leaching NO3-N emissions from manure deposited directly on pasture (kg NO3-N), by animal group

**Eq. 5.5.2‑6**

where

*Total\_N2O-Nindirectpasture* Total indirect N emissions from manure deposited directly on pasture (kg N2O-N year-1), by livestock type

**Eq. 5.5.2‑7**

where

*Total\_N2O-Npasture* Total N emissions from manure deposited directly on pasture (kg N2O-N year-1), by livestock type

## Manure C and N deposited on pasture by grazing animals for the ICBM/IPCC Tier 2 and soil N2O models

### Carbon

Manure C added to soil in grazing field *n* in year *t*:

**Eq. 5.6.1‑1**

where

*Cmodel\_pasture(t,field n)* TotalC added to soil from dung and urine deposited directly on pasture by grazing animals (kg C), specific to field *n* in year *t*

Note: this includes C added to soil from all livestock types grazing on field *n* in year *t*

*Cexcretion(t,field n)* Total amount of C in dung and urine deposited directly on pasture (kg C), specific to field *n* in year *t*; this is the sum of manure C excreted by all animals grazing on the field in year *t*, by livestock type

*Total\_CH4manure(t,field n)*Total CH4 emissions from dung and urine deposited directly on pasture (kg CH4), specific to field *n* in year *t*; this is the sum of manure CH4 emissions from the dung and urine deposited on this field by all grazing animals in year *t*

### Nitrogen

Manure N added to soil in grazing field *n* in year *t*:

**Eq. 5.6.2‑1**

where

*Nmodel\_pasture(t,field n)* Nadded to soil from dung and urine deposited directly on pasture by grazing animals (kg N)*,* specific to field *n* in year *t*

Note: this includes N added to soil from all livestock types grazing on field *n* in year *t*

*Total\_Nexcretion(t,field n)* Total amount of N in dung and urine deposited directly on pasture (kg N), specific to field *n* in year *t*

*Total\_N2O-Npasture(t,field n)* Total direct and indirect N2O emissions from dung and urine deposited directly on pasture (kg N2O-N), specific to field *n* in year *t*; this is the sum of all direct and indirect N2O losses from manure deposited on this field by all grazing animals in year *t*

*Total\_NH3\_Npasture\_adju(t,field n)* Total adjusted NH3 emissions from dung and urine deposited directly on pasture (kg NH3-N), specific to field *n* in year *t*; this is the sum of manure NH3 emissions from dung and urine deposited on this field by all grazing animals in year *t*, minus indirect N2O-N emissions via volatilization

*Total\_NO3-Nleachingpasture(t,field n)* Total leaching NO3-N emissions from dung and urine deposited directly on pasture (kg NO3-N year-1), specific to field n in year t; this is the sum of manure NO3 emissions from dung and urine deposited on this field by all grazing animals in year *t*

**Eq. 5.6.2‑2**

where

*Total\_Volumemanurepasture* Total volume of manure produced by grazing animals on pasture (kg manure year-1, 1000 kg wet weight), by livestock type

*Total\_Nexcretion* Total amount of N excreted by grazing animals on pasture (kg N year-1), by livestock type

*Ncontent* N content of excreta (urine + faeces; % wet weight) (**Table 6**)

## Conversions

For N2O-N to N2O, NH3-N to NH3 and NO3-N to NO3 conversions, please see **Section 4.10**

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**5.2 Manure carbon**

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**Table 6**

See **Section 2.8** for references

**Table 36**

See **Section 4.11** for references

**Table 42**

See **Section 4.11** for references

# Energy CO2 emissions

(by R. Kröbel)

**Note:** Some values need only be represented one time (e.g., Conversion of GJ of diesel to kg CO2, Conversion of kWh of electricity to kg CO2 emissions).

## Cropping emissions

**The emissions for each crop are calculated independently. Results will be associated with each crop.**

**Cropping emission results will be calculated on a yearly basis. To report these as monthly values, these will be prorated equally over the entire year (/12).**

### CO2 from fuel use

These equations are used to calculate emissions from fuel use. Use equations (**Eq. 6.1.1‑1**) for cropped land, including annual crops and perennial forages, and equation (**Eq. 6.1.1‑2**) for fallow land.

#### Cropped land

**Eq. 6.1.1‑1**

where

*CO2cropfuel* CO2 emissions from cropping fuel use (kg CO2 year-1)

*Efuel* Energy from fuel use (GJ ha-1) (**Table 50** by region, soil type, tillage, crop type; in Western Canada use “crops”, in Eastern Canada use crop type based on **Table 52**)

*areacrop* Area of crop (ha) (include annual crops and perennial forages, calculate each crop independently)

*DieselConversion* Conversion of GJ of diesel to kg CO2 (kg CO2 GJ-1)

For default, Holos uses 70 kg CO2 GJ-1 for *DieselConversion* (National Inventory Report 1990-2008).

#### Fallow land

**For Western Canada (fallow land) only:**

**Eq. 6.1.1‑2**

where

*Total\_CO2fallowfuel* Total CO2 emissions from fallowing fuel use (kg CO2 year-1)

*Efuel* Energy from fuel use (GJ ha-1) (**Table 50**, by region, soil type, tillage, “fallow”, crop type)

*areafallow* Area of fallow (ha)

### CO2 from herbicide manufacturing

These equations are used to calculate emissions from herbicide manufacturing. Use equations ( **Eq. 6.1.2‑1**) for cropped land, including annual crops and perennial forages, and equation (**Eq. 6.1.2‑2**) for fallow land.

#### Cropped land

**Eq. 6.1.2‑1**

where

*CO2cropherbicide* CO2 emissions from cropping herbicide production (kg CO2 year-1)

*Eherbicide* Energy for herbicide production (GJ ha-1) (**Table 51**, by region, soil type, tillage, crop type; in Western Canada use “crops”, in Eastern Canada use crop type based on **Table 52**)

*HerbicideConversion* Conversion of GJ for herbicide production to kg CO2 (kg CO2 GJ-1)

**For default, Holos uses 5.8 kg CO2 GJ-1 for *HerbicideConversion* (Dyer and Desjardins 2007).**

#### Fallow land

**For Western Canada (fallow land) only:**

**Eq. 6.1.2‑2**

where

*Total\_CO2fallowherbicide* Total CO2 emissions from fallow herbicide production (kg CO2 year-1)

*Eherbicide* Energy for herbicide production (GJ ha-1) (**Table 51**, by region, soil type, tillage, “fallow”, crop type)

### CO2 from nitrogen and phosphorus fertilizer production

**These equations are used to calculate emissions from N and (phosphorus) P fertilizer production. Use these equations for each fertilized crop, including annual crops, perennial forage and improved grassland/pasture.**

#### Nitrogen fertilizer production

**Eq. 6.1.3‑1**

**Eq. 6.1.3‑2**

where

*CO2Nfertilizer* CO2 emissions from N fertilizer production (kg CO2 year-1)

*N\_fert\_applied*N fertilizer applied (kg product ha-1)

*area* Area of crop fertilized (ha) (include annual crops and perennial forages and improved pasture if fertilized, calculate each crop independently)

*CO2eqgate* CO2 equivalent emission associated with N fertilizer production (kg CO2eq (kg product)-1) (**Table 48)**

*CO2eqappl* CO2 equivalent emission associated with N fertilizer application (kg CO2eq (kg product)-1) (**Table 48)**

#### Phosphorus fertilizer production

**Eq. 6.1.3‑3**

where

*CO2Pfertilizer* CO2 emissions from P2O5 fertilizer production (kg CO2 year-1)

*Pfertilizer* P fertilizer rate (kg product ha-1)

*CO2eqgate* CO2 equivalent emission associated with P fertilizer production (kg CO2eq (kg product)-1) (**Table 48)**

#### Potassium fertilizer production

**Eq. 6.1.3‑4**

where

*CO2Kfertilizer* CO2 emissions from P2O5 fertilizer production (kg CO2 year-1)

*Kfertilizer* K fertilizer rate (kg product ha-1)

*CO2eqgate* CO2 equivalent emission associated with K fertilizer production (kg CO2eq (kg product)-1) **Table 48**

#### CO2 from Liming application (IPCC 2006)

**The default EF of 0.12 for limestone from IPCC (2006) is being used.**

**Eq. 6.1.3‑5**

**Eq. 6.1.3‑6**

where

*CO2Liming* CO2 emissions from Liming application (kg CO2 year-1)

*MLiming* annual amount of calcic limestone (CACO3) (kg product yr-1)

*EFLiming* emission factor (kg C (kg limestone)-1)

*44/12* C to CO2 conversion

### CO2 from irrigation

**This equation is used to calculate emissions from irrigation use.**

**Eq. 6.1.4‑1**

where

*CO2irrigation* Total CO2 emissions from irrigation (kg CO2 year-1)

*area* area of crop irrigated (ha) (include annual crops and perennial forages and improved pasture if irrigated, calculate each crop independently)

*Irrigation* Amount of irrigation (mm ha-1 yr-1)

Pumptype CO2 emissions per unit of irrigation water applied: electric pump = 0.266 kg CO2 mm-1, natural gas pump = 1.145 kg CO2 mm-1**[[14]](#footnote-15)**

Tooltip:

1.0 *mm irrigation* = 0.0394 *inches irrigation*

This calculation encompasses surface irrigation systems / side-roll sprinkler systems / high pressure centre pivot sprinkler systems / low pressure centre pivot sprinkler systems using a single average.

### Total cropping emissions

Results should be totalled for each crop (annual crops, perennial forage and improved grassland/pasture) and fallow land.

**Eq. 6.1.5‑1**

where

CO2cropenergy CO2 emissions from cropping energy use (kg CO2year-1)

CO2fuel CO2emissions from cropping/fallow fuel use (kg CO2year-1)

CO2herbicide CO2emissions from cropping/fallow herbicide production (kg CO2year-1)

CO2Nfertilizer  CO2emissions from N fertilizer production (kg CO2year-1)

CO2Pfertilizer CO2emissions from P2O5 fertilizer production (kg CO2year-1)

CO2irrigation CO2emissions from irrigation (kg CO2year-1)

## Livestock emissions

**The emissions for each animal group are calculated independently. Results will be associated with animal group.**

**Livestock emission results will be calculated on a monthly basis.**

### CO2 from dairy

**This equation is used to calculate emissions for dairy based on the number of dairy cows.**

**(Assumes no energy emissions from other dairy animals.)** **Results will be associated with lactating dairy cows – each lactating group.**

**Eq. 6.2.1‑1**

where

*CO2dairy* Total CO2 emissions from dairy operations (kg CO2 year-1**) – for each lactating group**

*#cows* Number of lactating dairy cows (from dairy cows form)

*DairyCowConversion* kWh per dairy cow per year for electricity (kWh cow-1)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1)

*#days* Number of days in month (from dairy cows form)

**For defaults, Holos uses 968 kWh cow-1 for *DairyCowConversion* (Vergé *et al.* 2007)** **and province-specific values for *ElectricityConversion (*kg CO2 kWh-1) (Table 49). Dividing by 365 converts the yearly energy value to a daily value.**

### CO2 from swine

**This equation is used to calculate emissions for swine based on the number of sows and boars or finishers or growers or starters, depending on user-entry. Results will be associated with each pig group.**

**If sows and/or boars and/or finishers are entered, calculate CO2 emissions from each.**

**Eq. 6.2.2‑1**

**Eq. 6.2.2‑2**

**Eq. 6.2.2‑3**

**If only growers and/or starters are entered, calculate CO2 emissions from growers only.**

**Eq. 6.2.2‑4**

**If only starters are entered, calculate CO2 emissions from starters.**

**Eq. 6.2.2‑5**

where

*#pigs* Number of pigs

*#sows* Number of sows

*#boars* Number of boars

*#finishers* Number of finishers

*#growers* Number of growers

*#starters* Number of starters

All from swine forms.

**Eq. 6.2.2‑6**

where

*CO2swine* Total CO2 emissions from swine operations (kg CO2 year-1), for each pig group

*SwineConversion* kWh per pig per year for electricity (kWh pig-1)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1)

*#days* Number of days in month (from swine forms)

**For defaults, Holos uses 1.06 kWh pig-1 for *SwineConversion* (Dyer and Desjardins 2006)** **and province-specific values for *ElectricityConversion (*kg CO2 kWh-1) (Table 49). Dividing by 365 converts the yearly energy value to a daily value.**

### CO2 from poultry

**This equation is used to calculate emissions for poultry based on the barn capacity. Results will be associated with poultry group.**

**Eq. 6.2.3‑1**

**Eq. 6.2.3‑2**

where

*#animals* Number of animals

*CO2poultry* Total CO2 emissions from poultry operations (kg CO2 year-1) **– for each poultry group**

*barn\_capacity* Barn capacity (from poultry form)

*PoultryConversion* kWh per poultry placement per year for electricity electricity (kWh poultry placement-1 year-1)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1)

*#days* Number of days in month (from poultry form)

**For defaults, Holos uses 2.88 kWh poultry placement-1 year-1 for *PoultryConversion* (Dyer and Desjardins 2006) and province-specific values for *ElectricityConversion (*kg CO2 kWh-1) (Table 49). Dividing by 365 converts the yearly energy value to a daily value.**

### CO2 from housed beef

This equation is used to calculate emissions for housed beef cattle based on the number of cattle that are housed and the type of housing. Emissions will be allocated to the relevant beef cattle group **(cows, bulls or feedlot).**

**Eq. 6.2.4‑1**

where

*CO2housedbeef* Total CO2 emissions from housed beef operations (kg CO2 year-1), for each housed beef group

*#animals* Number of housed cattle

*HousedBeefConversion* kWh per cattle per year for electricity (kWh beef-1 year-1)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1)

*#days* Number of days in month (from beef form)

**For defaults, Holos uses 65.7 kWh beef-1 for an annual *HousedBeefConversion* (Dyer and Desjardins 2006) and province-specific values for *ElectricityConversion (*kg CO2 kWh-1) (Table 49). Dividing by 365 converts the yearly energy value to a daily value.**

## Manure spreading emissions

The manure spreading emissions for each animal group are calculated independently. Results will be associated with land-applied manure in soils/cropping section.

These equations are used to calculate emissions for fuel use in manure spreading.

### For liquid manure spreading

**Eq. 6.3.1‑1**

where

*Volumelandmanure* Volume of liquid manure applied to land (1000 litres)

*Nlandmanure*(*liquid)(animalgrp)*Total N (L) from land-applied liquid manure, by animal group, calculated using **Eq. 4.5.2‑6** for liquid dairy manure and **Eq. 4.5.2‑22** for liquid swine manure)

*Ncontent* N content of liquid manure (% wet weight), by manure management system (**Table 6**)

**Eq. 6.3.1‑2**

where

*CO2liquidmanure* CO2 emissions from liquid manure spreading (kg CO2 year-1)

*LiquidManureConversion* GJ of energy per 1000 litres of liquid manure applied (GJ 1000 litre-1)

*DieselConversion* Conversion of GJ of diesel to kg CO2 (kg CO2 GJ-1)

**For defaults, Holos uses 0.0248 GJ 1000 litre-1 (M. Wiens, La Broquerie project, University of Manitoba, personal communication) and 70 kg CO2 GJ-1 for *DieselConversion* (ECCC, 2022).**

**This equation is used for total emission summation.**

**Eq. 6.3.1‑3**

where

*Total\_CO2liquidmanure* Total CO2 emissions from liquid manure spreading (kg CO2 year-1)

### For solid manure spreading

**Eq. 6.3.2‑1**

where

*Volumelandmanure* Volume of solid manure applied to land (1000 kg)

*Nlandmanure*(*liquid)(animalgrp)* Total N (kg) from land-applied solid manure, by animal group, calculated using **Eq. 4.5.2‑6** for solid beef and dairy manure, **Eq. 4.5.2‑16** and **Eq. 4.5.2‑22** for solid manure from all other livestock groups)

*Ncontent* N content of solid manure (% wet weight), by manure management system (**Table 6**)

**Eq. 6.3.2‑2**

where

*CO2solidmanure* CO2 emissions from solid manure spreading (kg CO2 year-1)

*SolidManureConversion* GJ of energy per 1000 kg of solid manure applied (GJ 1000 litre-1)

**For defaults, Holos uses 0.0248 GJ 1000 litre-1 (M. Wiens, La Broquerie project, University of Manitoba, personal communication) and 70 kg CO2 GJ-1 for *DieselConversion* (ECCC 2022).**

**This equation is used for total emission summation.**

**Eq. 6.3.2‑3**

where

*Total\_CO2solidmanure* Total CO2 emissions from solid manure spreading (kg CO2 year-1)

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**Table 6**

See **Section 2.8** for references

**Table 48**

See **Section 2.8** for references

**Table 49**

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**Tables 50 & 51**

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Smith, E. Pers. Comm.

# Economics

Our team intended to update the economic component of Holos V3 for use in Holos V4, but provincial reporting has changed since V3 and is no longer compatible with our lookup tables. Our team liased with departmental collaborators to circumvent this issue, but work on this is still ongoing and yet to be finished. One of the main problems is to devise a system through which cost lookup tables are updated on a regular basis, which likely would require provincial buy-in. A further issue is that publicly available cost-of-production reports do not have the level of detail needed to calculate changes in costs due to changes in management that would lower GHG. Last but not least, the way livestock economics is calculated is so different from how GHG emissions are calculated that we have no vision yet of how to resolve the differences between the two. Regardless, we are committed to pursuing the further development of this component, and hope to provide updates in the future.

## Crops & grasslands

## Trees

## Beef

## **Net return, contribution margin calculations and considerations**

# Summations

(by R. Kröbel)

Following are the equations to sum emissions from all sources and to convert these emissions to CO2 equivalents (Mg) based on their global warming potential (**Table 54**).

## N2O

N2O emissions from land applied manure are included here.

### Direct soil N2O

**Eq. 8.1.1‑1**

where

*N2Odirectsoil*(*CO2eq*)Direct N2O emissions from soils (Mg CO2 eq year-1)

*N2Odirectsoil* Direct N2O emissions from soils (kg N2O year-1) (**Eq. 2.6.9‑24** or **Eq. 2.7.8‑24**)

*GlobalWarmingPotentialN2O* Global warming potential conversion factor for N2O (100 yr timeframe, IPCC 2015)

1000 Conversion from kg to Mg

### Indirect soil N2O

**Eq. 8.1.2‑1**

where

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (Mg CO2 eq year-1)

*N2Oindirectsoil* Indirect N2O emissions from soils (kg N2O year-1) (**Eq. 2.6.9‑24** or **Eq. 2.7.8‑24**)

### Direct manure N2O

**Eq. 8.1.3‑1**

where

*N2Odirectmanure*(*CO2eq*)Manure direct N2O emission from livestock (Mg CO2 eq year-1)

*Total\_N2Odirectmanure* Total manure direct N2O emission from livestock (kg N2O year-1) (**Eq. 2.6.9‑24** or **Eq. 2.7.8‑24**)

### Indirect manure N2O

**Eq. 8.1.4‑1**

where

*N2Oindirectmanure*(*CO2eq*)Manure indirect N2O emission from livestock (Mg CO2 eq year-1)

*Total\_N2Oindirectmanure* Total manure indirect N2O emission from livestock (kg N2O year-1) (**Eq. 2.6.9‑24** or **Eq. 2.7.8‑24**)

## Carbon

### Soil Carbon

**Eq. 8.2.1‑1**

where

*CO2soil*(*CO2eq*)CO2 emissions from soils (Mg CO2 eq year-1)

*CO2e(soil)/CO2soil* CO2 emissions from soils (kg CO2 year-1) (**Eq. 2.1.5‑2** or **Eq. 2.2.1‑105**)

1000 Conversion from kg to Mg

Different parameter names for single year carbon vs ICBM, and none in IPCC Tier2

### Shelterbelt and linear plantings carbon

**Eq. 8.2.2‑1**

where

*CO2shelterbelt*(*CO2eq*)CO2 emissions from tree plantings/shelterbelt (Mg CO2 eq year-1)

*Total\_CO2shelterbelt* Total CO2 emissions from tree plantings/shelterbelt (kg CO2 year-1) (from equation)

1000 Conversion from kg to Mg

TotalCO2shelterbelt not present

### Energy CO2

**Eq. 8.2.3‑1**

where

*CO2energy*(*CO2eq*)CO2 emissions from energy use (Mg CO2 eq year-1)

*Total\_CO2energy* Total CO2 emissions from energy use (kg CO2 year-1) (from equation)

1000 Conversion from kg to Mg

TotalCO2energy not present

### Enteric CH4

**Eq. 8.2.4‑1**

where

*CH4enteric*(*CO2eq*)Enteric CH4 emission from livestock (Mg CO2 eq year-1)

*Total\_CH4enteric* Total enteric CH4 emission from livestock (kg CH4 year-1) (**Eq. 3.4.2‑1**)

*GlobalWarmingPotentialCH4* Global warming potential conversion factor for CH4 (100 yr timeframe, IPCC 2006)

1000 Conversion from kg to Mg

### Manure CH4

**Eq. 8.2.5‑1**

where

*CH4manure*(*CO2eq*)Manure CH4 emission from livestock (Mg CO2 eq year-1)

*Total\_CH4manure* Total manure CH4 emission from livestock (kg CH4 year-1) (**Eq. 4.4.1‑1**)

1000 Conversion from kg to Mg

## Total emissions per farm

### Direct N2O – soils and manure

**Eq. 8.3.1‑1**

where

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (Mg CO2 eq year-1)

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (Mg CO2 eq year-1)

*N2Oindirectmanure*(*CO2eq*)Manure indirect N2O emission from livestock (Mg CO2 eq year-1)

### Indirect N2O – soils and manure

**Eq. 8.3.2‑1**

where

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (Mg CO2 eq year-1)

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (Mg CO2 eq year-1)

*N2Oindirectmanure*(*CO2eq*)Manure indirect N2O emission from livestock (Mg CO2 eq year-1)

### Methane – soils and manure

**Eq. 8.3.3‑1**

where

*CH4* (*CO2eq*)CH4 emission from the farm (Mg CO2 eq year-1)

*CH4enteric*(*CO2eq*)Enteric CH4 emission from livestock (Mg CO2 eq year-1)

*CH4manure*(*CO2eq*)Manure CH4 emission from livestock (Mg CO2 eq year-1)

### Carbon dioxide

**Eq. 8.3.4‑1**

where

*CO2*(*CO2eq*)CO2 emissions from the farm (Mg CO2 eq year-1)

*CO2soil*(*CO2eq*)CO2 emissions from soils (Mg CO2 eq year-1)

*CO2shelterbelt*(*CO2eq*)CO2 emissions from tree plantings/shelterbelt (Mg CO2 eq year-1)

*CO2energy*(*CO2eq*)CO2 emissions from energy use (Mg CO2 eq year-1)

### Farm sum

**Eq. 8.3.5‑1**

where

*CO2eqfarm* Total annual farm CO2 eq emissions (Mg CO2 eq year-1)

*N2Odirect* (*CO2eq*)Direct N2O emissions from the farm (Mg CO2 eq year-1)

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (Mg CO2 eq year-1)

*N2Odirectmanure*(*CO2eq*)Manure direct N2O emission from livestock (Mg CO2 eq year-1)

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# Expression of Uncertainty

(by R. Kröbel)

## Uncertainty associated with each emission category

Version 4 uncertainty estimates have been adopted from Version 3 until better estimates can be developed. The previous estimates of uncertainty were developed based on expert opinion for each of the categories of emission given in the Holos output (**Table 57**). A categorization system was developed and is listed in **Table 58**.

### Uncertainty estimate for net emission

To determine the overall uncertainty for the estimate of net GHG emissions from a specified set of farm conditions, the following equation was used:

**Eq. 9.1.1‑1**

where

*Uncertainty* Uncertainty associated with net farm emission estimate

*A* Emission estimate for each emissions category (Mg CO2equivalent – calculated in Summations section, equations **Eq. 8.1.1‑1** to **Eq. 8.2.5‑1**)

*a* Uncertainty estimate (**Table 58**, by uncertainty category associated with emission category and relative uncertainty in **Table 57**)

# Reporting

Holos results are provided in the reporting section at different levels of detail. In the simplified form (basic mode), Holos will provide an overview of the emissions associated with each selected production system and provide both a visual representation (graph), as well as numerical information in the text. Outputs can be explored as summarized CO2 equivalents (converted GHG emission on the basis of their global warming potential) or as individual GHG amounts. A link will bring the user to the detailed results. All model outputs can be exported into an excel file for further processing.

The detailed results (advanced mode) provides a summary of the annual emissions, sorted by land units and animal groups, as well as by emission source (direct and indirect N2O, enteric and manure CH4, Energy CO2, soil C change CO2, and upstream CO2). Direct N2O results primarily from land management, but also manure storage systems, enteric methane from ruminant animals, manure methane from all manure sources, energy CO2 from on-farm fuel use, soil C CO2 from either soil carCbon gain or losses, and upstream CO2 from fertilizer, pesticide and electricity production/generation. The latter is not part of the farm’s GHG budget, but are needed for C footprint assessments of specific commodities.   
**Note:** enabling additional columns provides the outputs of alternative enteric methane emission calculations.

Emission results can be explored as CO2 equivalents to compare the different emission sources or as direct amounts of GHG. A monthly breakdown is provided, either by summing daily emission estimates (methane), equal subdivision (energy CO2), or by distribution table (nitrous oxide). Soil C outputs and upstream emissions remain annual outputs and will not be available in the monthly overview. The emission results can be explored also visually by selecting the emissions pie chart, the overall emissions chart and the component emissions chart.

If the multi-year model mode is enabled, the result section includes a multi-year simulations tab which displays the C change graphs of all fields setup in the farm. Hovering with the mouse over any of the graphs will provide the information about the estimated C stock in a specific year (alongside the year and the current crop). Slowly moving the mouse diagonally to the more information link, or switching above from graph to grid, will change the model output to a table format that provides detailed information on the estimated C inputs, the individual estimated C pools and the change of the total.   
**Note:** if the IPCC Tier 2 C model is enabled (default option in the user settings), only soil C outputs are provided, but choosing the ICBM model instead also provides a suite of N outputs.   
**Note also:** the ‘Enabling columns’ on the left side permits choosing which columns to display.

For further exploration of the results, the model outputs estimates of production (a visualization of the user’s inputs or the models default data), the feed estimate report to provide a overview of the models livestock consumption rates, a way to double check model inputs on livestock weight and average daily gains. The manure management tab is a further means to check model inputs and to delve deeper into the models calculations by providing details on feed intake and excretions, as well as the emissions from the different stages of manure management. Last but not least, the economics tab provides a generalistic cost of (crop) production estimate based on provincial cost of production reports, however, the economic model at this time does not dynamically react to changes in the farm management (instead, the user will have to change the cost estimates in the field/cropping systems component interface).

# Appendices

## Residue removal and hay harvest

(by R. Kröbel)

### Calculation of dry matter weight per bale

This section determines the amount of dry matter in a harvested bale of straw or hay, which serves as an alternative user input for residue export/hay harvest.

**Eq. 11.1.1‑1**

**Eq. 11.1.1‑2**

where

*Weightbale(straw/hay)* Total weight of bale n (kg bale-1)

*DryMatter(straw/hay)* DM (kg DMbale-1)

*Moisturecontent* Moisture content of product at time of harvest (%)

*n* Number of bales harvested

### Storage of bales

Harvested bales are stored on the farm for further use as bedding or forage. No losses during storage are accounted for at this time. Straw bales are assumed to last **2 years**, as it is assumed that a permanent storage structure is not being invested in due to the low economic value of the product.

For hay bales, we assume a life span of **5 years**, as the higher value of the product, alongside a foreseeable requirement for long-term forage availability planning make investment into a long-term storage appears more likely. The user will be required to confirm the existence of a permanent storage structure, however, and unselecting the option will reduce the life span to 2 years.

**Eq. 11.1.2‑1**

**Eq. 11.1.2‑2**

where

*Storagestraw/haybales* Number of bales available on-farm (#)

## Bedding application rate calculator

(by A.W. Alemu)

### User-required inputs

For each management period **(# of days, # of animals known**):

* application frequency (daily, every second day, etc.)
* per each application (one single input per management period):
  + total # of bales used/total amount of wood-chip applied
  + specification whether bales were imported (yes/no) from outside the farm
    - in the case of YES: weight of a bale, and moisture content need to be specified
    - in the case of NO: information from the storage are used
  + wood-chips are assumed to be imported by default

### Calculated imports

**Eq. 11.2.2‑1**

where

*#bales* User-specified application rate

*Weightbale(straw)* Total weight of straw bale (kg bale-1)

*Baledrymatter* DM (%) from user input

**Eq. 11.2.2‑2**

**Eq. 11.2.2‑3**

where

*#daysManagementPeriod* User-specified length of management period (#days)

*#daysapplication frequency* User-specified application frequency (#days)

*BeddingMaterialapplied* Total bedding applied (kg)

*Beddingapplied(day)* Total bedding applied per day (kg)

*Beddingapplied(rate)* Total bedding applied per day and animal (kg)

## Feed requirement balance

(by R. Kröbel)

### Dry matter intake and forage requirement

**(This note should be included in the output file –**

**“DMI calculated based on gross energy requirements (IPCC 2019).”)**

**For all ruminant animals except beef calves, values for each animal group are calculated separately using the equations below.** For beef calves, DMI (kg head-1 day-1) is calculated according to **Eq. 3.1.2‑2**.

**Eq. 11.3.1‑1**

**Eq. 11.3.1‑2**

**Eq. 11.3.1‑3**

**Eq. 11.3.1‑4**

where

*DMIanimal(day)* DM intake per animal and day (kg head-1 day-1)

*GEI animal(day)*  Gross energy intake per animal and day (MJ head-1 day-1) calculated in **Eq. 3.1.1‑11**, **Eq. 3.2.1‑10** and **Eq. 3.3.1‑13**

*18.45* Conversion factor for gross energy per kg of DM (MJ kg-1)

*DMIanimalgroup(day)* DM intake per animal group and day (kg group-1 day-1)

*DMIManagementPeriod* DM intake per animal group during the entire management period (kg group-1 period-1)

*#animalManagementPeriod* User-specified number of animals in a management period (#days)

*#daysManagementPeriod* User-specified length of management period (#days)

*Carbonconcentration* C concentration of all plant parts (kg kg-1)

*Carbon UptakePasture(group, period, fieldn)*Amount of C foraged by an animal group during a management period from a specific pasture

**There is a limit to how much animals can consume in a day** based on the animal energy requirement. From this, a limit for Dry Matter Intake (*DMImax*) can be calculated:

**Eq. 11.3.1‑5**

where

*DMImax* DM intake per animal and day (kg head-1 day-1)

*FinalWeight* Final animal weight (kg animal-1)

*0.0225* Body weight intake limit (2.25%)

**If the calculated DMI fulfills the following condition:**

**Eq. 11.3.1‑6**

Users will be reminded to review whether they are providing animals with a diet that fulfills their daily energy requirements.

**Feed nitrogen use efficiency**

This needs to be done for each animal group for beef and dairy per month, excluding calves.

For all animals:

**Eq. 11.3.1‑7**

where

*NI* N intake (kg head-1 day-1)

*PI* Protein intake (kg head-1 day-1)

6.25Conversion from dietary protein to dietary N

Protein intake is calculated in Equation **Eq. 4.2.1‑1**.

**Eq. 11.3.1‑8**

where

*Neff* Feed N use efficiency (%)

*Nexcretion\_rate* N excretion rate (kg head-1 day-1)

The daily N excretion rate (kg N head-1 day-1) for beef and dairy cattle is calculated using **Eq. 4.2.1‑8** (adult animals) and **Eq. 4.2.1‑15** (calves), sheep using **Eq. 4.2.1‑18**, swine using **Eq. 4.2.1‑24**, pullets, broilers and layers using **Eq. 4.2.1‑28**, and other livestock using **Table 42**.

### Calculating pasture aboveground biomass from animal forage consumption

For grazed systems, *Cp* for field *n* in year *t* is estimated using Eq. X.X.X-X and *CptoSoil(t)*using Eq. X.X.X-X. When there is just a single grazing management period on field *n* in year *t*, the amount of C in the agricultural product (*Cp(t)*) is calculated based on the amount of forage biomass consumed by the grazing livestock and the amount of forage remaining in the field. When there are two or more grazing management periods on field *n* in year *t* (either consecutive or non-consecutive), *Cp(t)* is calculated based on the amount of forage consumed during all grazing periods plus the forage remaining at the end of the last grazing period only. For all grazing scenarios, *CptoSoil(t)* is estimated as the difference between the *Cp(t)*and the total forage C consumed by livestock in year *t*.

**Eq. 11.3.2‑1**

**Eq. 11.3.2‑2**

**Eq. 11.3.2‑3**

For a single grazing management period on field *n* in year *t*, *Cp(t)*is calculated using the equation below, considering the C consumed by the grazing livestock plus the C in leftover forage:

**Eq. 11.3.2‑4**

When there are two or more grazing management periods on field *n* in year *t*, *Cp(t)* for each period is calculated using the equation below for all management periods except the final period (for the final management period, **Eq. 11.3.2‑4** above is used):

**Eq. 11.3.2‑5**

The total aboveground biomass for all grazing management periods on field *n* in year *t* is calculated as:

**Eq. 11.3.2‑6**

**Eq. 11.3.2‑7**

**Eq. 11.3.2‑8**

where

*Carbon UptakePasture (group, period, fieldn)* Amount of C foraged from field *n*, by animal group and management period

*Carbon UptakePasture(period, fieldn)*Amount of C foraged from field *n* by all animal groups during a specific management period

*Carbon UptakePasture (fieldn)*Total amount of C foraged per year from field *n* (kg C)

*Carbon Exporthay (fieldn)*Total amount of C exported as baled hay per year from field *n* (kg C)

*Cp(t,period1)* Amount of C in agricultural product for a single grazing period or the final period when there are multiple grazing periods on field *n* in year *t* (kg ha-1)

*Cp(tperiod>1)* Amount of C in agricultural product for multiple grazing periods on field *n* in year *t* (kg ha-1), excl. the final grazing period

*Cp(t)* Total annual plant C in agricultural product for field *n* (kg ha-1)

*CptoSoil(t)* C added to the field’s soil from the aboveground biomass in year t (kg ha-1)

*Utilization* Utilization rate of aboveground biomass through animal grazing, which depends on the grazing system and grazing intensity, derived from the overall pasture productivity and stocking density (%)

*YieldPasture(t)* Total aboveground biomass yield for field *n* in year *t* (kg DM ha-1)

*Sp* Percentage of product yield returned to soil (user override)

*area* Area of field *n* (ha)

*Cptosoil* C input from product (kg ha-1)

## Estimates of production output equations

(by R. Kröbel)

Dairy, Beef, Sheep and Manure equations should be calculated monthly and summed for a yearly estimate.

Crop equation is calculated yearly only.

This also includes a calculation of total land area.

### Dairy

For each lactating group -

**Eq. 11.4.1‑1**

where

*Milk* Milk production for month (kg month-1)

*milk\_production* Milk production (kg head-1 day-1 )

*#cows* Number of cattle

*#days* Number of days in month

**Eq. 11.4.1‑2**

Derived from IDF 2015

where

FPCM Fat and protein corrected milk production for month (kg month-1)

Subtracting 0.19 from the crude protein value results in true protein required for Fat and Protein Corrected Milk. These values are found in **Section 3.2** for Dairy Cattle.

### Beef feedlots/stockers

For each beef group (backgrounding, finishing, stocker group) –

**Eq. 11.4.2‑1**

where

*Beef* Live weight of beef produced for month (kg) – from initial weight to final weight

*ADG* Average daily gain (kg head-1 day-1)

*#cattle* Number of cattle

*#days* Number of days in month

These values are found in **Section 3.1** for Beef Cattle.

### Sheep

For each sheep feedlot group -

**Eq. 11.4.3‑1**

where

*Lamb* Live weight of lamb/mutton produced for month (kg) – from initial weight to final weight

*ADG* Average daily gain (kg head-1 day-1)

*#sheep* Number of sheep

*#days* Number of days in month

These values can be found in **Section 3.3** for Sheep.

### Crops

For each crop –

**Eq. 11.4.4‑1**

where

*Harvest* Total crop yield (kg)

*Yield* Crop yield (kg ha-1)

*area* Area of crop (ha)

These values can be found in **Section 2.1.2** for C inputs.

### Land-applied manure N

For each animal group –

**Eq. 11.4.5‑1**

where

*Nlandmanure* Manure available for land application (kg N)

These values are found throughout the document in each animal section.

### Total land area

For entire farm –

**Eq. 11.4.6‑1**

where

*Farm\_area* Total farm area of all crops, fallow and grassland (native and seeded) (ha)

*area* Area of all crops, fallow and grassland (seeded and native) (ha)

Area of all crops (perennial and annual), fallow and grassland (seeded and native) should be included in this summation. These values are found in **Section 2.1.2** for C inputs.

**Add this note to the output –**

**Production estimate algorithms are still under development. Total land area includes only crop and grassland areas as entered by user.**

## Terminology

This section contains terminology used in the equations in the developer equation document.

### Emission Sources

**Soil N2O– direct:** direct emissions of N2O from N supplied to soil, in form of synthetic or organic N (the latter including crop residues and N mineralization)

**Soil N2O– indirect:** emissions of N2O from N that was leached (NO3) or volatilized (NH3), transported away from the farm, and subsequently converted to N2O

**Soil CO2:** Calculated from the change in soil C as a net-loss or net-gain. Photosynthetic C fixation and respiration are not output.

**Enteric CH4:** animal (primarily ruminant) digestion induced CH4 emissions

**Manure CH4:** CH4 emissions from manure handling in barn and storage, as well as upon application

**Manure N2O – direct:** emissions of N2O from manure handling in barn and storage, as well as upon application

**Manure N2O – indirect:** emissions of N2O from N that was leached (NO3) or volatilized (NH3), transported away from the farm, and subsequently converted to N2O

**Shelterbelt CO2:** Calculated from the change in soil C, as well as the living tree biomass, as a net-loss or net-gain. Photosynthetic C fixation and respiration are not output.

**Energy CO2:** On farm machinery use (fuel consumption), as well as use of pumps (irrigation)

**Upstream emissions:** Sum of emissions associated with the production of inputs (i.e., synthetic fertilizer, pesticides).

### Farm components

This refers to each specific farm operation, based on product or output. For example:

**Land managment**

* Field
* Crop rotation
* Shelterbelt

**Beef**

* Cow-calf
* Backgrounding
* Feedlot

**Dairy**

**Sheep**

* Sheep Feedlot
* Rams
* Lambs and Ewes

**Swine**

* Grower to Finish
* Farrow to Wean
* Iso Wean
* Farrow to Finish

**Poultry**

* Pullet Farm
* Chicken Multiplier Breeder
* Chicken Meat Production
* Turkey Multiplier Production
* Chicken Egg Production
* Chicken Multiplier Hatchery

**Other animals**

* Goats
* Deer
* Horses
* Mules
* Bison
* Llamas

**Infrastructure (likely to be expanded in future)**

* Anaerobic Digestion

### Group

This refers to a specific animal group, with which one or more management periods are associated. Each livestock type contains one or more livestock components, which in turn contain one or more animal groups, e.g., the beef livestock type includes the beef cow-calf, beef stockers and backgrounders and beef finisher components, each of which contains a number of animal groups, e.g., the beef finisher component contains the heifer and steer animal groups.

### Tillage

Intensive tillage – complete burial of residue; vertical mixing of the soil

Reduced tillage – one or few tillage passes with most residue retained on the surface; horizontal mixing of the soil

No-till – no tillage at any point in the rotation except at seeding; no mixing of the soil

### Perennials

Native – native grassland that was never tilled

Seeded grassland – grassland that was seeded and is reseeded on occasion to readjust species composition, may be irrigated

Tame grass/legume/mixed – pasture that is frequently reseeded, irrigated, and fertilized

## Sources of error

This lists possible sources of error if Holos is not used as designed/intended.

* Growing crops without fertilizer application will reduce N2O unrealistically.
* Carbon storage can be over- and underestimated depending on the starting value and the simulation length.

For cattle and sheep, energy requirements for pregnancy and protein retained for fetal development are prorated over the entire year. This can be a problem if animals aren’t entered for 12 months but the user expects a correct emissions estimate if only entering in a complete gestation (e.g., 9 months or 5 months).

## References

IDF 2015. International Dairy Federation. A common carbon footprint approach for dairy-The IDF guide to standard life cycle assessment methodology for the dairy sector. Bulletin of the IDF No. 479/2015. <https://www.fil-idf.org/wp-content/uploads/2016/09/Bulletin479-2015_A-common-carbon-footprint-approach-for-the-dairy-sector.CAT.pdf>

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. Available at: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

**Table 42**

See **Section 4.11** for references

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1. This equation was changed to run with RS (MJ m-2) rather than Rs (cal cm-2). [↑](#footnote-ref-2)
2. The reference ETo is defined and calculated using the FAO Penman-Monteith equation (Allen et al., 1998). [↑](#footnote-ref-3)
3. Water loss by interception occurs at days when precip occurs and does never exceed potential evapotranspiration (Andren, 2004). [↑](#footnote-ref-4)
4. The daily irrigation amount applied to the crop is a user provided value or it is assumed that the amount is the difference between precipitation and evapotranspiration (if precipitation is smaller than ET). [↑](#footnote-ref-5)
5. The C concentration value of 0.45 kg C kg-1 plant biomass is derived from Baron et al. (2002) for mixed pasture. This value has been applied to all crop types included in the model. [↑](#footnote-ref-6)
6. The Tier 2 Steady state method may be applicable to other land uses, but this will require further development and parameterisation than provided in IPCC (2019), section 5.2.3. [↑](#footnote-ref-7)
7. This approach is not intended to be used for estimation of dead organic matter. Compilers should apply the dead organic matter methods in section 5.2.2. [↑](#footnote-ref-8)
8. The C concentration value of 0.45 kg C kg-1 plant biomass is derived from Baron et al. (2002) for mixed pasture. This value has been applied to all crop types included in the model. [↑](#footnote-ref-9)
9. “A reduction of 40% due to crust cover may be applied only when a thick, dry crust is present. Thick dry crusts occur in systems in which organic bedding is used in the barn and is allowed to be flushed into the liquid storage tank and solids are not seperated from the manure stream and further the surface is not exposed to regular heavy precipitation that may disrupt the surface. Sources: Aguerre et al. (2012); Nielsen et al. (2013); VanderZaag et al. (2008)” (IPCC 2019). [↑](#footnote-ref-10)
10. From IPCC (2019), Table 10.17: “New information suggests that a solid cover reduces CH4 emissions by 25 to 50% (range: 0 to 90%). Sources: Amon et al. (2006), Amon et al. (2007); Clemens et al. (2006); Guarino et al. (2006), Matulaitis et al. (2015), Misselbrook et al. (2016), VanderZaag et al. (2009), Hou et al. (2015), VanderZaag et al. (2008)” (IPCC 2019). For Holos, a default value of 25% reduction in manure CH4 emissions for systems with a solid cover has been assumed. The option for the user to choose a specific cover type and associated reduction factor has also been included in the model for the following cover types: straw (26%), woodchips (29%), expanded clay (11%), hydrophobic powder (ammonium phosphate, ammonium sulphate and hydrophobic silica) (81.5%) (Source: values calculated from data presented in VanderZaag et al., 2008; VanderZaag et al., 2009). [↑](#footnote-ref-11)
11. This restriction is required because the adjustment factor under negative *T* will be a negative value. [↑](#footnote-ref-12)
12. From Odirile et al. (2021): for primary clarifier (PC) sludge: C conc. (%, wet weight basis) = 1.28%; for microsieve (MS) sludge: C conc. (%, wet weight basis) = 18.02%; average C conc. = 9.65%. From Serbanescu et al. (2017): average C conc. = 8.45%. Average across all studies = (9.65 + 8.45) / 2 = 9.1% = 0.091 kg kg-1. [↑](#footnote-ref-13)
13. Based on a moisture content of 74%: C conc. = 12.35% (0.12 kg kg-1, wet wt basis). [↑](#footnote-ref-14)
14. These values were calculated based on [AB Ag cost of irrigation](http://demofarm.ca/2016%20Irrigated%20Crop%20Production%20Update/0935%20-%20Bennett%20rb_ICPU_20jan2016.pdf) and converted from cost to energy used. This was then converted to CO2 emissions (NIR 1990-2008) . The average of the values for electricity and natural gas was taken. This assumes a low pressure pivot, 43 HP, 15 inches of irrigation. Values for electricity and natural gas were obtained from the ECCC (2022): electricity – 0.200 kg CO2 kWh-1 (Tbl A13-1 of the NIR); natural gas = 14.12 tC/ TJ (Tbl A4-2 of the NIR). [↑](#footnote-ref-15)