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**Holos V4.0**

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**Algorithm Documentation**

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**Navigation of the document**

Section, Equation and Table numbers are hyperlinked throughout this document, bringing you to the original source. If you’d like to return to the previous location from there, “ALT + ←” will take you back.

**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).

**Upcoming features**

Model features that are not currently supported by Holos V4 can be requested by members of the Holos user community via our [GitHub repository](https://github.com/holos-aafc/Holos/issues), which also details current feature requests and issues relating to the model. To request a new feature or report an issue/bug, click on the link above and then the ‘New issue’ button on the top-right, and select the appropriate option. **Please note:** there is no guarantee that all requested features will be added to a future version of Holos, as new features will be added based on Holos team priorities, user priorities and available resources.

Table of Contents

[List of Figures 7](#_Toc188351423)

[List of Tables 8](#_Toc188351424)

[1 Introduction 12](#_Toc188351425)

[1.1 Purpose of the Holos model 12](#_Toc188351426)

[1.2 Target audience 13](#_Toc188351427)

[1.3 Principles of model development 14](#_Toc188351428)

[1.4 Workshops and outreach 15](#_Toc188351429)

[1.5 Structure of this document 15](#_Toc188351430)

[1.6 Required input parameters 16](#_Toc188351431)

[1.7 References 22](#_Toc188351432)

[2 Land Management 23](#_Toc188351433)

[2.1 Introductory Carbon Balance Model (ICBM) 23](#_Toc188351434)

[2.2 Intergovernmental Panel on Climate Change (IPCC) Tier 2 Carbon Model 48](#_Toc188351435)

[2.3 Shelterbelt and lineal tree planting 62](#_Toc188351436)

[2.4 Water budget model 67](#_Toc188351437)

[2.5 Nitrous oxide emission factor calculation (IPCC Canada Tier 2) 68](#_Toc188351438)

[2.6 Multi-year estimation of nitrous oxide (adapted from Liang et al. 2020 with N carryover) for ICBM 74](#_Toc188351439)

[2.7 Multi-year estimation of nitrous oxide (adapted from Liang et al. 2020 with N carryover) for IPCC Tier 2 carbon model 93](#_Toc188351440)

[2.8 References 116](#_Toc188351441)

[3 Livestock enteric methane emissions 130](#_Toc188351442)

[3.1 Beef cattle 130](#_Toc188351443)

[3.2 Dairy cattle 137](#_Toc188351444)

[3.3 Sheep 142](#_Toc188351445)

[3.4 Swine, Poultry and other livestock 146](#_Toc188351446)

[3.5 Scaling up to yearly estimates 147](#_Toc188351447)

[3.6 References 148](#_Toc188351448)

[4 Livestock manure: CH4 and N2O emissions from livestock housing and manure storage 152](#_Toc188351449)

[4.1 Manure carbon and CH4 emissions from livestock manure 156](#_Toc188351450)

[4.2 Manure nitrogen and direct N2O emissions from livestock manure in housing 165](#_Toc188351451)

[4.3 Indirect N2O emissions from livestock manure during housing and storage 173](#_Toc188351452)

[4.4 Total emissions 189](#_Toc188351453)

[4.5 Manure available for land application, addition to an anaerobic digestion system or export 190](#_Toc188351454)

[4.6 Emissions from land application of stored manure 197](#_Toc188351455)

[4.7 Manure C and N for the ICBM/IPCC Tier 2 and soil N2O models 213](#_Toc188351456)

[4.8 Anaerobic digestion of livestock manure and crop residues 215](#_Toc188351457)

[4.9 Emissions from land application of raw and stored digestate 235](#_Toc188351458)

[4.10 References 240](#_Toc188351459)

[5 Animals in grazing situations 252](#_Toc188351460)

[5.1 Enteric CH4 emissions from grazing animals on pasture 252](#_Toc188351461)

[5.2 Manure C and CH4 emissions from livestock manure deposited on pasture 252](#_Toc188351462)

[5.3 Direct N2O emissions from livestock manure deposited on pasture 252](#_Toc188351463)

[5.4 Indirect N2O emissions from manure deposited on pasture for all livestock types 254](#_Toc188351464)

[5.5 Total emissions 258](#_Toc188351465)

[5.6 Manure C and N deposited on pasture by grazing animals for the ICBM/IPCC Tier 2 and soil N2O models 259](#_Toc188351466)

[5.7 Conversions 260](#_Toc188351467)

[5.8 References 261](#_Toc188351468)

[6 Energy CO2 emissions 262](#_Toc188351469)

[6.1 Cropping emissions 262](#_Toc188351470)

[6.2 Livestock emissions 265](#_Toc188351471)

[6.3 Manure spreading emissions 267](#_Toc188351472)

[6.4 References 269](#_Toc188351473)

[7 Economics 271](#_Toc188351474)

[7.1 Crops and grasslands 271](#_Toc188351475)

[7.2 Trees 271](#_Toc188351476)

[7.3 Beef 271](#_Toc188351477)

[7.4 Net return, contribution margin calculations and considerations 271](#_Toc188351478)

[8 Summations 272](#_Toc188351479)

[8.1 N2O 272](#_Toc188351480)

[8.2 Carbon 273](#_Toc188351481)

[8.3 Total emissions per farm 274](#_Toc188351482)

[8.4 References 275](#_Toc188351483)

[9 Expression of Uncertainty 276](#_Toc188351484)

[9.1 Uncertainty associated with each emission category 276](#_Toc188351485)

[10 Reporting 277](#_Toc188351486)

[11 Appendices 279](#_Toc188351487)

[11.1 Residue removal and hay harvest 279](#_Toc188351488)

[11.2 Bedding application rate calculator 279](#_Toc188351489)

[11.3 Feed requirement balance 280](#_Toc188351490)

[11.4 Estimates of production output equations 284](#_Toc188351491)

[11.5 Terminology 286](#_Toc188351492)

[11.6 Sources of error 288](#_Toc188351493)

[11.7 References 288](#_Toc188351494)

[12 Acknowledgements 289](#_Toc188351495)

# List of Figures

|  |  |
| --- | --- |
| **#** | **Name** |
| **Figure 1** | Overview of the IPCC Tier 2 steady state method |
| **Figure 2** | Schematic representation of the Canadian N2O emission factor calculation |
| **Figure 3** | Schematic overview of the Holos N-budget. |
| **Figure 4** | Carbon and nitrogen flows in manure management for livestock in Canada |
| **Figure 5** | Flow diagram representing the structure of the anaerobic digestion component in Holos |

# List of Tables

|  |  |  |  |
| --- | --- | --- | --- |
| **#** | **Name** | **GitHub Link** | **Format** |
| **Table 1** | Values for the coefficients *a*, *b*, *c*, *d*, and *e* required to calculate growing degree day driven crop coefficients (*Kc*) (from Martel et al. 2021) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_1_Growing_Degree_Crop_Coefficients.csv) | CSV |
| **Table 2** | Climate normal periods | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_2_Climate_Normal_Periods.csv) | CSV |
| **Table 3** | *rc* factor – Alberta, Saskatchewan, Manitoba only | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Calculators/Tillage/TillageFactorCalculator.cs) | C# code |
| **Table 4** | Percentage of total annual irrigation water applied by month for each province/region in Canada (average values across 2010 and 2012) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_4_Percentage_Total_Annual_Irrigation_Water_Applied.csv) | CSV |
| **Table 5** | Carbon input residue allocation by crop type | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_5_Carbon_Input_Residue_Allocation_By_Crop_Type.csv) | CSV |
| **Table 6** | Manure types and default composition | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_6_Manure_Types_And_Default_Composition.csv) | CSV |
| **Table 7** | Relative biomass allocation coefficients, lignin and nitrogen contents for different crops | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_7_Relative_Biomass_Information.csv) | CSV |
| **Table 8** | Globally calibrated model parameters to be used to estimate SOC changes from mineral soils with the IPCC (2019) Tier 2 steady-state method | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_8_Globally_Calibrated_Model_Paramters_To_Estimate_SOC_Changes.csv) | CSV |
| **Table 9** | Default values for nitrogen and lignin contents in crops for the IPCC (2019) Tier 2 steady-state method | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_9_Default_Values_For_Nitrogen_Lignin_In_Crops.csv) | CSV |
| **Table 10** | Default values for carbon to nitrogen ratios, nitrogen, and lignin contents in livestock manure for the IPCC Tier 2 steady-state method (from IPCC (2019), Table 5.5C) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_10_Default_Values_For_Steady_State_Method.csv) | CSV |
| **Table 11** | Coefficients for aboveground biomass estimation for shelterbelt tree species | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_11_Coefficients_For_AGB_Estimation_For_Shelterbelt_Trees.csv) | CSV |
| **Table 12** | Shelterbelt carbon accumulation lookup table by hardiness zone | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_12_Shelterbelt_Carbon_Accumulation_Lookup_By_Hardiness_Zone.csv) | CSV |
| **Table 13** | Soil nitrous oxide emission factors (N2O EF) as influenced by source of nitrogen, soil texture, tillage practice and crop type in Canada (adapted from Liang et al. 2020) and N2O reduction factors based on fertilizer application method | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Soil/Table_13_Soil_N2O_Emission_Factors_Provider.cs) | C# code |
| **Table 14** | Coefficients used for the Bouwman et al. (2002) equation | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Calculators/Nitrogen/N2OEmissionFactorCalculator.cs) | C# code |
| **Table 15** | Default soil N2O emission breakdown | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Soil/Table_15_Default_Soil_N2O_Emission_BreakDown_Provider.cs) | C# code |
| **Table 16** | Livestock coefficients for beef cattle and dairy cattle | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_16_Livestock_Coefficients_BeefAndDairy_Cattle_Provider.cs) | C# code |
| **Table 17** | Feeding activity coefficients (*Ca*) for beef cattle and dairy cattle | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_17_Beef_And_Dairy_Cattle_Feeding_Activity_Coefficients.csv) | CSV |
| **Table 18** | Diet coefficients by livestock type and diet for beef cattle and dairy cattle | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_18_26_Diet_Coefficients_For_Beef_Dairy_Sheep.csv) | CSV |
| **Table 19** | Additive reduction factors for beef cattle and dairy cattle | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_19_Additive_Reduction_Factors_Provider.cs) | CSV |
| **Table 20** | Examples of *NEmf* content of typical diets fed to cattle for estimation of dry matter intake (IPCC 2019, Table 10.8a) | [Link](https://github.com/holos-aafc/Holos/blob/a30b5d2682c8b6c9b96ec31069a04e006e2ab9e0/H.Core/Providers/Feed/DietProvider.cs#L427) | C# code |
| **Table 21** | Average milk production for dairy cows from 1990 to 2020, by province (ECCC 2022) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_21_Average_Milk_Production_For_Dairy_Cows_By_Province.csv) | CSV |
| **Table 22** | Livestock coefficients for sheep | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_22_Livestock_Coefficients_For_Sheep.csv) | CSV |
| **Table 23** | Feeding activity coefficients for sheep | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_23_Feeding_Activity_Coefficient_Sheep_Provider.cs) | C# code |
| **Table 24** | Lamb daily weight gain | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Animals/Table_24_Lamb_Daily_Weight_Gain_Provider.cs) | C# code |
| **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 and management coefficients, 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 CH4 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, *Fracvolatilization* values are estimated within Holos and 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_Poultry_Other_Livestock_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 |
| **Table 46** | Parameters used for the calculation of biogas and methane production using an anaerobic digestion system | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_46_Parameters_For_Calculating_Biogas_Methane_Production_In_AD_System.csv) | CSV |
| **Table 47** | Default values for separation coefficients (fraction in solid fraction) for solid-liquid separation of digestate | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/AnaerobicDigestion/Table_47_Solid_Liquid_Separation_Coefficients_Provider.cs) | C# code |
| **Table 48** | Carbon footprint at plant gate for different fertilizer blends (US numbers) based on Brentrup et al. (2018) | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_48_Carbon_Footprint_At_Plant_Gate_For_Direct_Fertilizer_Blends.csv) | CSV |
| **Table 49** | Electricity conversion values, by province and year | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_49_Electricity_Conversion_Values_By_Province.csv) | CSV |
| **Table 50** | Fuel energy requirement (*Efuel*) 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_50_Fuel_Energy_Requirement_Estimates_By_Region.csv) | CSV |
| **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, W m-2) | [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 |
| **Table 60** | Utilization rate lookup table for livestock grazing | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Core/Providers/Plants/Table_60_Utilization_Rates_For_Livestock_Grazing_Provider.cs) | C# code |
| **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 |
| **Table 63** | Indoor dairy barn temperatures | [Link](https://github.com/holos-aafc/Holos/blob/main/H.Content/Resources/Table_63_Indoor_Barn_Temperatures.csv) | CSV |

# Introduction

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

## 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 (EFs) 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 (e.g., 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 there is the option to test the results of scientific experiments in a whole-farm context (under ‘what is?’ 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 ‘what if?’ questions). Holos V4 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 (V4) of the model, the Holos team recognizes the need to further facilitate the holistic assessment of farms with additional components (e.g., on-farm wetlands, riparian buffers, woodlots, and renewable energy generation), as well as the need to provide additional capabilities (e.g., economics and ecosystem services modules). Although these components are not featured in Holos V4, the future collaborative development of Holos (V5 and thereafter) has been facilitated by the open source availability of the V4 model code. Thus, we are continually searching for opportunities to involve the expertise of other groups in- and outside of AAFC to facilitate the improvement and expansion of future versions.

## Target audience

There is not one single target user group for Holos, 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 aims 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 detailed data inputs that reflect the experimental setup.

Policy makers are likely to utilize the model for policy implementation, where farmers (landowners) input their farm operation data into the model and use the outputs (potentially through a certified third 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 (landowner) 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, as 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 releases 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) as well as the lookup values and default data used to populate the model. 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 model’s software code is shared in an open source environment on our [GitHub repository](https://github.com/holos-aafc/Holos). 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 create and share a framework for collaborative development with respect to software architecture. 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 these 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 ([sign up here](https://github.com/holos-aafc/Holos/discussions)), 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 three-day ‘Sustainability of Canadian Agriculture’ conference with several hundred attendees, 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. During this conference, our half-day Holos training session has attracted over a hundred participants in recent years.

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 participants. Training can also be provided through an online platform, although troubleshooting is more limited and there is less opportunity for feedback.

One element that can improve online training, in particular self-training, are our Holos training materials, which include step-by-step pdf training guides and a series of video tutorials (available on our [GitHub](https://github.com/holos-aafc/Holos/tree/main) page). The team is available to host trainees at the Lethbridge Research and Development Centre and also offers opportunities for students as part of the Canadian universities Co-op student program.

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 (**Chapter 2**, also the recommended first step in 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, thus, the default option in Holos. The final carbon section is the updated shelterbelt component, from where we plan to continue into the water budget sub-model (this will be added after the release of V4). With the nitrogen (N) model, we describe the multi-year N budget approach (compliant with the National GHG inventory as far as the emissions 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.

In these sections, the model estimates emissions from livestock and the manure they produce, tracking C and N flows from excretion through to land application. **Chapter 4** also includes an anaerobic digestion (AD) component, into which the user can ‘load’ manure and crop residues, with this sub-model tracking C and N losses throughout the AD process and the production of biogas, heat and electricity. In **Chapter 6** 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 V4). The end of the document details the summation of the results, uncertainty estimates and reporting considerations, before finishing with the appendices.

## Required input parameters

General considerations:

* **Metric or imperial units of measurement are chosen at the start, and apply to the complete run.   
  Note: the imperial option is currently unavailable but will be re-enabled in a future version of Holos.**
* **There is a French and an English version of the interface.**
* **All information entered saves instantaneously and continuously.**
* **The user can select each farm component multiple times.**
* **The default soils data are limited to the areas designated as containing agricultural land by Statistics Canada.**
* **When adjusting inputs in an already saved farm, press ‘reload data from previous screen’ on the Details screen to update the results**
* **In the options, model defaults can be reset to the latest lookup-table values in the settings menu.**

### 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 (as 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 N2O emissions from agricultural soils (**section 2.5, 2.6, and 2.7**), and the estimation of emissions from livestock (**Chapters 3, 4 and 5**).

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.

**Note:** the user can specify soil data for individual fields on the ‘Soil’ tab for the relevant field – this will override the default soil data used for the entire farm.

Also in the Map Location screen, 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 (SK), 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 the climate data required by Holos varies depending on the model component. Daily climate data are needed for the calculation of NH3 losses and animal performance, as well as in the land management component to calculate the soil moisture, but the model is set up to run with monthly climate normals if daily data are 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 uses the following constant value:

*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/>

For future scenarios, Holos calculates monthly climate normals for the projection period based on daily NASA data (when there is an internet connection) or using in-built Holos climate normals for each SLC polygon (when no internet connection is available). Using the NASA climate data, Holos calculates climate normals for the 2000-current year period as a default; using the SLC-specific climate normals, the calculation period is 1990-2017. The climate normals are calculated as follows:

**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 Inputs

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 product (harvest losses)) and belowground (i.e., roots and root exudates/extra-root material) 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 inputs for these parameters, the model will use default data, although these are only approximate representations.  
   - default crop yields are based on yields from the Small Area Data (SAD) database for the specified crop and year (<https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210000201>). When the user selects ‘Average Yield’ as the Yield Assignment Method, Holos calculates this as the average of the yield for all crops in the rotation as specified under Step 3 in the Component Selection screen.  
   - default fertilization rates (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 annual crops (except root crops), and straw return is assumed to be 100% (all straw remaining in the field). For perennial crops, 30% of the root biomass is assumed returned to the soil in all years except the final year of the stand, when this value is 100%. Harvest losses are assumed to be 2% for annual crops and 35% for perennial crops.
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 by the user.
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 for the average model user.

#### Crop rotation

The crop rotation component 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 within 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 each year. The crop management practices specified are automatically applied to all fields for the entire duration of the simulation, although these can be modified later in the ‘Timeline’ screen.

#### Shelterbelt

For the shelterbelt component, the current state of C accumulation can be calculated using row length, number of trees 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 estimates of the amount of C stored within the tree and 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 (by animal group), 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 to the farm. 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) shorter-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.

Preset animal numbers, weights and weight gain, housing system, manure management and diets are also present for all beef components, but note that only one management period is entered as default for the backgrounding and finishing 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 options. 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 several EFs 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 CH4 estimates.

#### Pork

The pork/swine production system offers different components (or combinations thereof) that represent typical 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 set up to represent expected changes in diet as animals age.

Note that the enteric CH4 emissions from pork are calculated using a per animal emission rate, specific to different animal groups and weight categories. These EFs can be adjusted when the user selects the “Show Additional Information” option, although these should only be changed based on scientific evidence, By default, the model assumes that all animals are housed in barns but there is also the option to place the animals on pasture. 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 subsequent 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 poultry 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 due to a lack of available data, Holos does not currently include Canada-specific default management periods for these animals. 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 estimated, so animals can be placed on pasture, but currently no biomass consumption rates are available for these animal groups.

## References

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

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/>

Martel, M, Glenn. A., Wilson, H., and Kröbel, R., 2018. Simulation of actual evapotranspiration from agricultural landscapes in the Canadian Prairies. Journal of Hydrology: Regional Studies 15, 105-118. <https://doi.org/10.1016/j.ejrh.2017.11.010>

Turc, L., 1961. Water requirements assessment of irrigation, potential evapotranspiration: simplified and updated climatic formula. Ann. Agron. 12, 13–49 (in French).

**Table 1**

Martel, M., Glenn, A., Wilson, H., Danielescu, S., Kröbel, R., Smith, W., McConkey, B., Guest, G., and Janzen, H., 2021. A parsimonious water budget model for Canadian agricultural conditions. Journal of Hydrology: Regional Studies 36, August 2021, 100846. <https://doi.org/10.1016/j.ejrh.2021.100846>

# Land Management

## Introductory Carbon Balance Model (ICBM)

(by R. Kröbel and A.W. Alemu)

The Introductory Carbon Balance Model (ICBM) is a simplified two-pool C model developed to estimate the 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 (SLC) 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 downloads a 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 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 the 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 as 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., leave the land fallow), irrigate a crop for improved 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).

The ICBM requires a starting point for initialization. **Holos V4 relies on the assumption that soil organic carbon (SOC) is in a steady state/reference condition in the initial year of the simulation (default = 1985) for the rotation and management practices described (Kröbel et al. 2016).** Multi-year crop rotations complicate this initialization because of differing C inputs that depend on the crop type. As such, the C input used is 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 30-year monthly climate normal 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 for each day 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-defined)

*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 uses 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 the soil temperature on 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 uses the following constant value:

*SoilTopThickness* 250 mm (if no soils database value is available)

###### 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 on 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 on a daily basis 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 (%) (**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)

###### Actual Evapotranspiration

**Eq. 2.1.1‑27**

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

**Eq. 2.1.1‑28**

If *VolSoilWaterContent* < *alfa*\**WiltingPoint*

**Eq. 2.1.1‑29**

**Eq. 2.1.1‑30**

where

*Kr* Soil coefficient (dimensionless)

*alfa* Minimum water storage fraction of WiltingPoint

*ETa* Actual evapotranspiration (mm day-1)

Holos V4 uses the following constant value:

*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 uses 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**

If *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 uses the following constant values:

*rs* 0.42 mm3 mm-3

rwp 0.18 mm3 mm-3

##### Climate Factor

*re\_crop* is 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 uses the following constant value:

*Reference adjustment* 0.10516

#### Tillage Factor (*rc*)

Using a dynamic C model (default start year = 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 option**s: No tillage, Reduced tillage, Intensive tillage

The tillage regime can be modified for each year of the cycle and is based on user input. For the Prairie Provinces (Alberta (AB), SK, and Manitoba (MB)), 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 (AB, SK and MB), 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 the termination year, the reduced tillage factor is applied for the relevant soil type (**Table 3**). For non-prairie provinces, the constant values in the box below are used.

Holos V4 uses 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 and for each year of the simulation period.

**Eq. 2.1.1‑47**

where

*re* Climate/management factor

*rc* Tillage factor

#### Annual moisture availability

**Eq. 2.1.1‑48**

where

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

*AnnualMoistureAvailability* Total moisture available to the crop (used for lookup in **Table 7**)

### C inputs

Carbon inputs are calculated for each field and 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% of the root biomass).**

Note that irrigated and rainfed crops can have different biomass allocation coefficients. The Holos model includes specific biomass fractions for irrigated crops where available, and uses 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 harvested biomass after this losses took place. Therefore, the user-provided yield is adjusted 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 (i.e., hay). The total yield estimate (including harvest losses) is then adjusted to account for moisture content to provide a dry matter yield value for the total aboveground biomass produced on the field.

**Eq. 2.1.2‑1**

*where*

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

*Yield* Crop yield (kg wet weight ha-1, default or user-defined)

*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 (default or user-defined)

**Note:** When grazing animals are present on a field and the user specifies a custom yield for the year(s) in which grazing animals are present, *Yield x Sp/100* is equal to zero, assuming that the yield entered by the user represents the total aboveground biomass produced on the field (i.e., biomass consumed + leftover biomass). If the user specifies a custom yield for a perennial field in a year(s) when no grazing animals are present and no harvest activity is specified, the custom yield should represent the total aboveground biomass (kg wet weight), and the Yield x Sp/100 is equal to zero.

**Note**: For green manure crops (incl. cover crops), the yield entered should represent the total aboveground biomass (wet weight for main crops and dry weight for cover crops), which is considered by Holos to be ‘product’. As all of this biomass remains in the field, there is no harvest loss, and so Holos estimates the *Cp* for green manure crops as: *Yield \* Sp/100 \* 0.45*.

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)

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

*Area* Area of field (ha)

*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 or swathing is chosen as the harvest option for a main crop (meaning the user is entering a total aboveground biomass value instead of a grain yield), the residue fractions for product and straw are combined to form a single product coefficient, *Rp*, and **Eq. 2.1.2‑7** is omitted from the calculations. For the ‘Green manure’ harvest method, we assume all crop biomass remains in the field, thus the default ‘Product returned to soil’ value is set to 100%. For ‘Swathing’, where we assume livestock are placed on the field to grazed the swathed vegetation, the default ‘Product returned to soil’ value is set to 30% to represent the proportion of total aboveground biomass that remains in the field after grazing has concluded (i.e., a 70% utilization rate). For both ‘Green manure’ and ‘Swathing’, we assume that the *Yield* entered by the user represents the total aboveground biomass and we also assume a 0% harvest loss (as no biomass is removed from the field).

Holos V4 uses 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 (with the exception of ‘Grass silage’, which is a perennial, therefore *Cr* and *Ce* for this crop are calculated according to **section 2.1.2.6.2**), 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: barley silage, grass silage, oat silage, silage corn, triticale silage and wheat silage.

**Note:** in the Holos interface, under Step 2 on the Component Selection screen, if the user is ‘growing’ a silage crop, they should ideally select the appropriate crop from the ‘Silage’ options in the drop down crop menu. If the user selects a non-silage crop and then chooses the ‘Silage’ option as the ‘Harvest method’ under Step 3, the soil C calculations will still be correct.

**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 uses the following constant values:

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

*SP* 2% (BC Ministry of Agriculture 2015)

*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 assume 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 bare fallow (In the Canadian prairies), the user is requested to input that as a main crop. Thus, the overall yield and the main crop biomass fraction have to be adjusted to represent the cover crop that replaces the 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, the product (*Rp*) and straw (*Rs*) biomass fractions are combined into *Rp*. 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* values.

Holos V4 uses 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

For root crops (**Table 7**), as the “root” is the product, the methodology is modified as described 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 uses the following constant values:

*Carbonconcentration* 0.45 kg kg-1

*SP* 0%

*Ss* 100%

#### Perennial crops

**Handling perennial crops**

Perennial crops (‘Forage for seed’, ‘Rangeland (native), ‘Seeded grassland’, ‘Tame grass’, ‘Tame legume’, ‘Tame mixed (grass/legume)’) 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 of 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.

**For all perennial crops, it is assumed that 30% of the root biomass is turned over (input) annually. When the user specifies a native rangeland or continuous perennial crop that lasts until the end of the simulation period, 30% of the root biomass/C is added to the soil each year (incl. the final year of the simulation). When the user adds a perennial crop as part of a multi-crop rotation and a different crop is ‘grown’ on the field after the perennial crop, 100% of the perennial root biomass/C is added to the soil upon termination of the perennial crop.** Extra-root input is calculated annually with the complete allocation coefficient.

##### Aboveground biomass

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

**In all years where a perennial crop is grown and the user does not specify any harvest operation and no animals are grazed on the field, the user should change the percentage of ‘Product returned to soil’ to 100% on the Residue tab on the Component Selection screen in the Holos interface.**

**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).   
**Note:** When grazing livestock are present on the field and the user has specified a custom yield value for the year(s) when grazing livestock are present, *Sp* is calculated as: *1-Utilization/100*

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).   
**Note:** When grazing livestock are present on the field and the user has specified a custom yield value for the year(s) when grazing livestock are present, *Sp* is calculated as: *1-Utilization/100*

*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*=1):**

**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 C ha-1 year-1 (i.e., root biomass must be equal to or greater than 1,000 kg DM ha-1 yr-1) (M.-N. Thivierge, AAFC, pers. comm.)

*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) – this value derived from data provided by M.-N. Thivierge (AAFC). **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**)

**Note:** To calculate the root C inputs (*Cr*) for the final year of a perennial stand, i.e., when a different crop is planted in the following year and *Sr* = 100%, the following calculation is used: *Cr(finalyearofstand) = (Cr(t-1)/3)\*10*

Holos V4 uses 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

##### Supplemental Hay

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 field-1)

*Baleweight* Weight of hay bale (kg wet weight) – 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 is handled as an annual crop with Yield=0, and for Western Canada with a no-till tillage factor (0.6 - 0.8 according to soil zone). The *re­­\_crop* calculation (**2.1.1.1**) also assumes Yield=0. The user will be asked whether they 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 detailed 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 uses 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 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 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 emissions related to manure application 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 on 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 Canada, 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 of C inputs and C loss), and this steady state is 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 different C inputs (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:** product from root crops is considered to be 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 uses the following constant value:

*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

*re* Climate/management factor

Holos V4 uses the following constant values:

*hag* 0.125

*hbg* 0.3

*hm* 0.31 (Kätterer & Andrén, 1999)

*ky* 0.8

*ko* 0.00605

#### 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 is applied to all fields on the farm. Entering this value will override the default 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 calculates C dynamics from the 1985 steady state start year (or the steady state for a different user-defined starting year). 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. 2.1.3‑7** or based on a measured initial SOC value as in **Eq**. **2.1.3‑10**. For the steady state starting point, average C input values will be used (**Eq. 2.1.3‑1** - **Eq. 2.1.3‑3**). For all subsequent years, 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**

**Eq. 2.1.3‑14**

**Eq. 2.1.3‑15**

**Eq. 2.1.3‑16**

**Eq. 2.1.3‑17**

**Eq. 2.1.3‑18**

**Eq. 2.1.3‑19**

where

*Yag* Young pool soil organic C – aboveground (kg C ha-1) at the beginning of the year

*Ybg* Young pool soil organic C – belowground (kg C ha-1) at the beginning of the year

Ym(t) Young pool soil organic C – manure (kg C ha-1) at the beginning of the year

*YoungPoolCag(t)* Young pool soil organic C – aboveground (kg C ha-1) at the end of the year with fresh residues included

*YoungPoolCbg(t)* Young pool soil organic C – belowground (kg C ha-1) at the end of the year with fresh residues included

*YoungPoolCm(t)* Young pool soil organic C – manure (kg C ha-1) at the end of the year with fresh residues included

*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) at the end of the year, with fresh residues included

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

Holos V4 uses 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. 2.1.3‑20**

**Eq. 2.1.3‑21**

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.

### C 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 combined with 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 real world C change estimates), 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)
* 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 tillage – no tillage at any point in the rotation except at seeding; no mixing of the soil

#### Converting carbon to CO2 equivalents

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

*CO2esoil(month)* CO2 change for soils (kg CO2e month-1), by month

*CO2e(soil)* CO2 change for soils (kg CO2e year-1)

*12* Number of months per year

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

(by R. Kröbel)

The IPCC Tier 2 steady-state method is a three sub-pool steady-state C model that provides a method for estimating soil C stock changes in the 0-30 cm layer of mineral soils in cropland remaining cropland.[[6]](#footnote-7) This 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***. In Holos V4, this ***is the default approach for the estimation of soil C stock changes***.

### 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 for a period of 5-20 years prior to the start of the inventory (or longer if data are available). During this spin-up period, if the user has specified a single tillage regime during the simulation period, this same tillage regime is assumed for the spin-up period (i.e., conventional tillage, reduced tillage or no-till); if the user specifies two or more tillage regimes during the simulation period, Holos assumes reduced tillage for the spin-up period. The initialisation methodology is described in **section 2.2.3**. A proportion of biomass C (C input to the soil) is transferred to the soil litter, and then divided into fraction *β*, which 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).

A diagram of a flowchart

Description automatically generated

**Figure 1.** Overview of the IPCC Tier 2 steady state method. Source: derived from 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 finely 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 must 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. 2.2.2‑7** below). Compilers 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** in this algorithm document). The type of tillage applied within each grid cell or region must be compiled to determine the correct value for the 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 biomass DM (*AGDM(T)*) for crop T (Crop(T))

*slope* From **Table 9**

*intercept* From **Table 9**

*Yield* Crop yield (kg 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 biomass DM added to the soil for crop *T* (kg DM ha-1)

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

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

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

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

*Sp* Percentage of product returned to soil. For grazed annual fields (with swathed or standing crop biomass), *Sp = 1-Utilization/100*

*T* Crop or forage type

**Eq. 2.2.2‑4**

IPCC (2019), Eq. 5.0H

where

*AGR(T)* Annual total amount of aboveground crop biomass remaining in the field 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)

**For crops using the ‘Cash crop’ harvest method:**

**Eq. 2.2.2‑5**

Derived from IPCC (2019), Eq. 5.0H

**For crops using the ‘Swathing’, ‘Silage’ or ‘Green manure’ harvest method (where there is only ‘product’ that includes all aboveground biomass, i.e., grain + straw/residue):**

**Eq. 2.2.2‑6**

Derived from 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. 2.2.2‑5** 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)* Root-to-shoot ratio = ratio of belowground root biomass to aboveground shoot biomass (grain + straw/residue) 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

**Eq. 2.2.2‑7**

IPCC (2019), Eq. 5.0H

where

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

*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**)

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

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

#### For crops not in the NIR

Currently, for crops that are not included in the NIR, soil C inputs are calculated using the ICBM.

**Eq. 2.2.2‑8**

*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. 2.2.2‑9**

**Eq. 2.2.2‑10**

*For root crops.*

**Eq. 2.2.2‑11**

**Eq. 2.2.2‑12**

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**

##### 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 2.1.2.6**

##### Fallow

Follow methodology in **section 2.1.2.7**

##### Manure

Follow methodology in **section 2.1.2.8**

##### Total input for non-NIR crops

**Eq. 2.2.2‑13**

where

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

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

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

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

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

*Area(T)* Total annual area harvested of crop *T* (ha yr-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 > 45 °C (i.e., the maximum average air temperature), set *Ti* to 0

**Eq. 2.2.3‑3**

IPCC (2019), Eq. 5.0F

where

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

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

*PETi* 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 *mappeti* is >1.25, set the value of *mappeti* for the month to 1.25 for non-irrigated systems (i.e., *mappeti* does not exceed 1.25). Set *wi* to 0.775 for months with irrigation.

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

**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 these 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 to 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**, respectively; 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 active SOC sub-pool (year-1) (**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) (**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) (**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) (**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) (**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), calculated using **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) (**Table 9**) for default values, otherwise compile country-specific values)

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

*f6* Fraction of slow sub-pool decay products transferred to the passive sub-pool (proportion) (**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, set the value of *mappeti* for the month to the estimated ratio; if the ratio is >1.25, set the value of *mappeti* for the month to 1.25; set *wi* for months with irrigation to 0.775.

#### Calculate the 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 (*wfac*)

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

**Repeat steps 2.2.5.1 to 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*) using **Eq. 2.2.3‑1** and the values for maximum monthly temperature for decomposition (*tmax*), optimum temperature for decomposition (*topt*) and the monthly average temperature (*tempi*).

**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 (*tfac*) 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 SOC sub-pool

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

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

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

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 to 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 (*Activey*)

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 to 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 supplies a custom soil C content value for the farm, a run-up period is still required to determine the sizes of the individual carbon pools. For this purpose, Holos uses average default yields (10 yr average ahead of the start year) and thus calculates the pool fractionation after 5 yrs (the time frame for the run-up period 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. 2.2.3‑13**)

*Slowyi* Slow sub-pool SOC stock in year *y* for grid cell or region (t C ha-1) (**Eq. 2.2.3‑15**)

*Passiveyi* Passive sub-pool SOC stock in year *y* for grid cell or region (t C ha-1) (**Eq. 2.2.3‑17**)

#### 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 is 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 shelterbelt component in Holos 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 provided the platform for this component and the estimates for other provinces. For the calculations and models outputs, the following underlying rules are present and unchangeable:

* Ecodistrict-specific lookup tables are used for the respective SLC polygons in the province of Saskatchewan.
* An area-weighted average was calculated for each plant hardiness zone that overlaps with those ecodistricts with available 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 a single 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 added to a single row, but estimates for these 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., a 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 dead trees), 15%, 30%, 50%, and 100% (i.e., all trees are dead - C values are 0 t km-1), the respective growth rates (or lack thereof) will be derived from the lookup tables.
* It is assumed that if trees die, they do so in the first year. Outputs are limited to the number of trees that remain 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)

*∑planted tree count(all species in a row)* Number of trees originally planted into the linear planting

*∑live tree count (all species in a row)* Number of trees alive for all species in a linear planting

For custom mortality values that fall between the levels in the lookup tables, *MortalityLow* and *MortalityHigh* are used. For example, for a custom mortality of 10%, the *MortalityLow* lookup is 0% and the *MortalityHigh* lookup is 15%. *MortalityLow* and *MortalityHigh* are defined in this way so as 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 (SK) 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*) (t C km-1 yr-1) and Total Living Biomass Carbon (*TLBClookup*) (t 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 as follows:

**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* Biomass of 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 (SK) 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 backward 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 stock in the living biomass of the user-defined shelterbelt (kg C shelterbelt-1)

Holos V4 uses the following constant values:

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

*Standard length* 1 km

### Total C 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**

where

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

### 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**). 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.

## 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 soil texture, where not specified in Table 13, has no effect (RF=1)**
* **For all perennial 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 EF [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-lying 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, where 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 EF 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

**Eq. 2.5.3‑1 is not currently in use**, as it would require the user to be able to specifiy multiple soil textures within a single field, which is not currently possible in Holos.

**Eq. 2.5.3‑1**

**Eq. 2.5.3‑2**

Liang et al. (2020); Pelster et al. (2023)

where

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

*RF\_TXj* Soil texture modifier (with ‘*j’* being coarse, 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 land unit

*1/0.645* Fraction of growing season emissions of total annual emissions (Pelster et al. 2023)

### 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* EF 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 to 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 (i.e., pasture that is fertilized and/or irrigated).

**When the 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 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 the product (kg N kg product-1), see **Table 48**

The default fertilizer application calculation is utilized when no information is supplied by the user (fertilizer amounts cannot be smaller than 0 kg N ha-1), but a fertilization application is added in the user interface.

**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)

*Soil\_test\_N* N available in the soil at the time of planting (kg N ha-1), user-defined

*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 uses the following constant values:

*Fertefficiency* 0.5 (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 7**)

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

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

*Ne* N concentration in the extra root material (kg kg-1) (until suitable data are available from the literature, the root N concentration 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

**For annual crops:**

**Eq. 2.5.6‑7**

**For perennial forages:**

**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)

#### 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 from Liang et al. 2020 with N carryover) for ICBM

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

A screenshot of a computer screen

Description automatically generated

**Figure 3:** Schematic overview of the Holos N-budget.

**Note:** 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 at 25 kg N. Pools carried over are not considered in the emissions calculations and are merely tracking N surpluses or deficits over time.

### 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 (i.e., 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* (estimated using **Eq. 2.5.5‑5 or Eq. 2.5.5‑6**, 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 uses the following constant value:

*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* (user-defined)

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

### Crop residue N inputs

This section 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 the amount of N released from the N pool through the decomposition of the C fraction is calculated.

*To calculate the starting AG N pool*

**Eq. 2.6.2‑1**

Crop residue N is added to the N pool corresponding to the young C pools, but the N contained in the young pool fraction that is decomposed in correlation with the respective C pool is subtracted.

**Eq. 2.6.2‑2**

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. 2.5.6‑2**

*StrawN* N content of the straw returned to the soil (kg N ha-1), calculated in **Eq. 2.5.6‑3**

*re* Climate/management factor

*ky* Decomposition rate constant for young pool

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

*To calculate the young residue aboveground pool size*

**Eq. 2.6.2‑3**

*To calculate the starting BG N pool*

**Eq. 2.6.2‑4**

**Eq. 2.6.2‑5**

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)

*To calculate the young residue belowground pool size*

**Eq. 2.6.2‑6**

**Calculation of N exported with crop residues**

**Eq. 2.6.2‑7**

where

*NCropResidues\_export(t, field n)* N in crop residues exported from field *n* in year *t* (kg N ha-1)

*AGDMexported(T)* Exported abg biomass for crop *T* (kg DM ha-1) from field *n* in year *t*, see **Eq. 2.2.2‑3**

*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 deposited directly on a field by grazing livestock) and anaerobic digestate, after all direct and indirect N losses related to land application are estimated in **sections 4.7.2, 4.9.7.2 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**

**Eq. 2.6.3‑3**

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 all farm-produced and imported manure applied to land, including leftover manure), **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

This section calculates the mineralization of N from residues in correlation with the decomposition of the respective residue C fraction (i.e., the young pools) and the N release by the soil C pool (i.e., the old pool). N released is added to the mineral 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**

If N\_CropResidues(t,field n) <0, N\_CropResidues(t,field n) = 0

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 uses the following constant value:

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

### Direct emissions

**This section calculates direct N2O emissions 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 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 (in line with the Canadian N2O emission factor methodology)
* 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 during the perennial phase, including in the year of termination (for pasture that is directly reseeded without interruption the perennial RF is maintained)
* The EF adjustment for tillage is specific to the tillage operation for the year in which the emissions are calculated
* Emissions from 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* EF 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,field n)* Direct N2O emissions (kg N2O-N ha-1) resulting from the sum of crop residue emissions exported from field *n* 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 (see below)  
**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 (i.e, compost), 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 4.6.1**. 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,field n)* NO emissions (kg NO-N ha-1) resulting from from the sum of crop residue emissions exported from field *n* 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 uses the following constant value:

*NOratio* 0.1

### 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)

**This section calculates indirect N2O emissions due to leaching/runoff from the 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** for land-applied stored manure (farm-produced and imported), **section 4.9.4** for land-applied digestate and **section 5.4.4** for manure deposited directly on pasture by grazing animals.

**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* EF 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 types)

*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 uses the following constant value:

*EFleach* 0.011 (IPCC 2019)

##### 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* EF 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 types)

*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 have removed the accounting of CRN (crop residual nitrogen) from the calculation (**Eq. 2.6.6-4** and **Eq. 2.6.6-9**) to avoid double-counting. This is because CRN becomes part of the soil C 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

**This section calculates indirect N2O emissions due to volatilization from the 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* EF 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 types)

*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 uses 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 types)

*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 equal to 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 C change and crop growth

**This section 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

*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**)

*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 uses the following constant value:

*Microbedeath* 0.20 (expert opinion M. Gorzelak, AAFC)

### Total emissions

#### Nitrogen losses from a field

##### Nitrous Oxide

**This section calculates 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 section recalculates the N2O emissions on a yearly basis.**

**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 the 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 into which the user can enter the percentage of yearly soil N2O emissions allocated to that month. The sum of monthly emissions should equal 100%.

The equations below are calculated for each crop (including annual crops, perennial forages, fallow and improved grassland/pasture), and for mineralized N.   
**Note:** these monthly percentages do not apply to land-applied manure or digestate.

##### N2O

**Eq. 2.6.9‑32**

where

*N2O \_\_\_\_\_* Direct N2O emissions from a specific 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 each month (see **Table 15** for default values)

#### Budgeting of Nitrogen

##### Input

These inputs are calculated before any emissions or other losses are considered.

**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

The equation below relates to the end of the N cycle (**section 2.6.7**) after all other calculations have been completed.

**Eq. 2.6.9‑37**

## Multi-year estimation of nitrous oxide (adapted from 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)

Nitrogen inputs in synthetic fertilizer application 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 (i.e., 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) applied to field *n* (estimated using **Eq. 2.5.5‑5 or Eq. 2.5.5‑6**, 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 uses the following constant value:

*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 differently to 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

**This section 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 the 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. 2.2.2‑5** or **Eq. 2.2.2‑6**

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

#### For crops not in the NIR

*This section 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 (kg 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, calculated using **Eq. 2.2.2‑3**

*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

This section calculates the mineralization of N from residues in correlation with the decomposition of the respective residue C fraction. It 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 draws 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 (kg N ha-1 year-1)

*CropR-N(t,field n)* Total organic N input (kg 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 (kg 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* (kg 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 (kg N ha-1)

**Eq. 2.7.3‑4**

IPCC (2019), Eq. 5.0B

where

*Activey* Active sub-pool SOC-N stock in year *y* (kg N ha-1)

*Activey-1* Active sub-pool SOC-N stock in the previous year (kg N ha-1)

**Eq. 2.7.3‑5**

IPCC (2019), Eq. 5.0C

where

*SlowNy* Slow sub-pool SOC-N stock in year *y* (kg N ha-1)

*CropR-N(t,field n)* Total organic N input (kg N ha-1)

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

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

*ActiveNy*\* Steady state active sub-pool SOC-N stock given conditions in year *y* (kg 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)

*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 the previous year (kg N ha-1)

*SlowNy\** Steady state slow sub-pool SOC-N stock given conditions in year *y* (kg N ha-1)

**Eq. 2.7.3‑7**

IPCC (2019), Eq. 5.0D

where

*PassiveNy* Passive sub-pool SOC-N stock in year *y* (kg 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* (kg 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* (kg 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) (**Table 8**)

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

**Eq. 2.7.3‑8**

IPCC (2019), Eq. 5.0D

where

*PassiveNy-1* Passive sub-pool SOC-N stock in the previous year (kg N ha-1)

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

*Activey-1* Active sub-pool SOC-N stock in the previous year (kg N ha-1)

*SlowNy-1* Slow sub-pool SOC-N stock in the previous year (kg N ha-1)

*SlowNy\** Steady state slow sub-pool SOC-N stock given conditions in year *y* (kg N ha-1)

*PassiveNy-1* Passive sub-pool SOC-N stock in the previous year (kg N ha-1)

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

#### Calculate N Input to the active sub-pool for each year of the inventory period

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

The N input to the active soil N 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. 2.2.3‑3** 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 (*wfac*)

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

Repeat steps **2.2.5.1** to **2.2.5.3** to to calculate the water effect (*wfac*) 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*) 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* to 0.**

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

The annual temperature effect on decomposition (*Tfac*) 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 N Sub-pool

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

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

##### Steady state stock for the passive sub-pool SOC-N stock (*PassiveNy\**)

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* > 1, then set the value of *kp* to 1 in the equation for calculating *PassiveNy*.**

**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. 2.2.3‑10**.

##### 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 *SlowNy*.**

**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. 2.2.3‑9**.

##### 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 (*ActiveNy*)

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* > 1, then set the value of *ka* to 1 in the equation for calculating *ActiveNy*.**

**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 supplies a custom soil C content value for the farm, a run-up period is still required to determine the sizes of the individual carbon pools. For this purpose, Holos uses average default yields (10-yr average ahead of the start year) and thus calculates the pool fractionation (active/slow/passive) after 5 yrs (the time frame for the run-up period 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 (kg C ha-1)

*ActiveNyi* Active sub-pool SOC-N stock in year *y* for grid cell or region (kg N ha-1)

*SlowNyi* Slow sub-pool SOC-N stock in year *y* for grid cell or region (kg N ha-1)

*PassiveNyi* Passive sub-pool SOC-N stock in year *y* for grid cell or region (kg 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 uses 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**

where

*SOC-Nyi* SOC-N stock at the end of the current year *y* for grid cell or region (kg N ha-1)

*ActiveNyi* Active sub-pool SOC-N stock in year *y* for grid cell or region (kg N ha-1) (**Eq. 2.7.3‑4**)

*SlowNyi* Slow sub-pool SOC-N stock in year *y* for grid cell or region (kg N ha-1) (**Eq. 2.7.3‑6**)

*PassiveNyi* Passive sub-pool SOC-N stock in year *y* for grid cell or region (kg N ha-1) (**Eq. 2.7.3‑8**)

##### Stock change factor (*F-NSOCi*) for each grid cell or region

**Eq. 2.7.3‑15**

where

*F-NSOCi* Annual stock change factor for mineral soils in grid cell or region *i* (kg N ha-1)

*SOC-Nyi* SOC-N stock at the end of the current year *y* for grid cell or region (kg N ha-1)

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

##### Total change in N stock (*ΔNMineral*)

The overall change in the amount of N that is stored within all SOC in all of the farm’s fields (N stock) is calculated by multiplying the stock change factor (*F-NSOCi*) by the area of all fields of the farm or region *i* (*A*) that are calculated using the IPCC Tier 2 steady-state method.

**Eq. 2.7.3‑16**

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* (kg N ha-1)

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

### Direct emissions

**This section calculates direct N2O emissions for each field and year independently. The following assumptions apply:**

* Emissions are calculated based on the specified farm soil texture.
* The soil texture, where not specified in **Table 13**, has no effect (RF = 1).
* Emissions from different N sources are calculated separately.
* Atmospheric deposition, if specified, is treated as synthetic fertilizer.
* The EF adjustment for tillage is specific to the tillage operation for the year in which the emissions are calculated
* 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.
* 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.
* N2O emissions from the decay of residues containing biologically-fixed N are included.
* 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).
* Manure emissions are calculated only for the field where the manure was applied.
* Manure emissions from manure exports are allotted to the farm of residue origin.

#### 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* EF 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,field n)* N2O emissions (kg N2O-N ha-1) resulting from from the sum of crop residue emissions that have been exported from field *n* 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 (see below)  
**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 types)

*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 4.6.1**. 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,field n)* NO emissions (kg NO-N ha-1) resulting from from the sum of crop residue emissions exported from field *n* 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 uses 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)

**This section calculates indirect N2O emissions due to leaching/runoff from the 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 (farm-produced and imported) via leaching are estimated in **section 4.6.4**, in **section 4.9.4** for land-applied digestate and **section 5.4.4** for manure deposited directly on pasture by grazing animals.

**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* EF 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 types)

*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 uses 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* EF 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 types)

*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 have removed the accounting of CRN (crop residual nitrogen) from the calculation to avoid double-counting (**Eq. 2.7.5-4 and Eq. 2.7.5-9**). This is because CRN becomes part of the soil C 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

**This section calculates indirect N2O emissions due to volatilization from the 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/organic 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**

**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* EF 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 types)

*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 uses 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 (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,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 equal to 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 C change and crop growth

**This section 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*

*CropNdemand* Crop N uptake in the current year

*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)

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

**Eq. 2.7.7‑16**

**If *NmicrobeN(t,field n)* ≤ 0**

Holos V4 uses the following constant value:

*Microbedeath* 0.20 (expert opinion M. Gorzelak, AAFC)

**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*

### Total emissions

#### Nitrogen losses from a field

##### Nitrous Oxide

**This section calculates 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 section recalculates the N2O emissions on a yearly basis.**

**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 into which the user can enter the percentage of yearly soil N2O emissions allocated to that month. The sum of monthly emissions should equal 100%.

The equations below are calculated for each crop (including annual crops, perennial forages, fallow and improved grassland/pasture), and for mineralized N.   
**Note:** these monthly percentages do 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 each month (see **Table 15** for default values)

#### Budgeting of Nitrogen

##### Input

These inputs are calculated before any emissions or other losses are considered.

**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

The equation below relates to the end of the N cycle (**section 2.7.7**) after all other calculations have been completed.

**Eq. 2.7.8‑32**

## References

**2.1 ICBM**

Andrén, O. and T. Kätterer. 1997. ICBM: The Introductory Carbon Balance Model for exploration of soil carbon balances. Ecological Applications 74: 1226-1236.

Baron, V.S., Mapfume, E., Dick, A.C., Naeth, M.A., Okine, E.K., and Chanasyk, D.S., 2002. Grazing intensity impacts on pasture carbon and nitrogen flow. Journal of Range Management 55(6), 535-541.

BC Ministry of Agriculture (2015) Farm Mechanization Factsheet. Forage Harvesting, Storage and Feeding Losses – The Mechanical Efficiencies Involved in Converting Hay to Meat. British Columbia Ministry of Agriculture, Order No. 240.100–4. <https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/farm-management/structures-and-mechanization/200-series/240100-4_forage_harvesting_-_storage_and_feeding_losses.pdf>.

Bolinder, M.A., O. Andrén, T. Kätterer, & L.E. Parent. 2008. Soil organic carbon sequestration potential for Canadian Agricultural Ecoregions calculated using the Introductory Carbon Balance Model. Canadian Journal of Soil Science 88: 451-460.

Bolinder, M.A., H.H. Janzen, E.G. Gregorich, D.A. Angers, & A.J.VandenBygaart. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems and Environment 118: 29-42.

Gan, Y.T., C.A. Campbell, H.H. Janzen, R.L. Lemke, P. Basnyat, & C.L. McDonald. 2009. Carbon input to soil from oilseed and pulse crops on the Canadian prairies. Agriculture, Ecosystems and Environment 132: 290-297.

Janzen, H., 2017. Personal communication

Janzen, H.H., K.A. Beauchemin, Y. Bruinsma, C.A. Campbell, R.L. Desjardins, B. H. Ellert and E.G. Smith. 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems 67: 85-102.

Kätterer, T., L. Andersson, O. Andrén, and J. Persson. 2008. Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm. Nutrient Cycling in Agroecosystems 81: 145-155.

Kätterer, T. and O. Andrén. 2009. Predicting daily soil temperature profiles in arable soils in cold temperate regions from air temperature and leaf area index. Acta Agriculturae Scandinavica Section B – Soil and Plant Science 59: 77-86. <https://doi.org/10.1080/09064710801920321>

Kröbel, R., M.A. Bolinder, H.H. Janzen, S.M. Little, A.J. Vandenbygaart, and T. Kätterer. 2016. Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM). Agricultural Systems 143: 76–85.

Rotz, C.A. and R.E. Muck. 1994. Changes in Forage Quality during Harvest and Storage. In: Forage Quality, Evaluation, and Utilization, Eds. G.C. Fahey, Jr. et al. Am. Soc. Agron., Madison, WI. pp. 828-868.

Soil Landscapes of Canada Working Group, 2010. Soil Landscapes of Canada version 3.2. Agriculture and Agri-Food Canada. (digital map and database at 1:1 million scale). <http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html>

Thorpe, J., 2011. Vulnerability of Prairie Grasslands to Climate Change. Limited Report, Saskatchewan Research Council, SRC Publication No. 12855-2E11. Saskatoon, SK, Canada. <https://www.parc.ca/rac/fileManagement/upload/12855-2E11%20Vulnerability%20of%20Grasslands%20to%20climate%20change.pdf>

**2.2 IPCC TIER 2**

Baron, V.S., Mapfume, E., Dick, A.C., Naeth, M.A., Okine, E.K., and Chanasyk, D.S., 2002. Grazing intensity impacts on pasture carbon and nitrogen flow. Journal of Range Management 55(6), 535-541.

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/>

Ogle, S. M., Swan, A. & Paustian, K. (2012) No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems and Environment 149: 37-49.

Parton, W. J., Schimel, D. S., Cole, C. V. & Ojima, D. S. (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51(5): 1173-1179.

Paustian, K., Agren, G. & Bosatta, E. (1997) Modelling litter quality effects on decomposition and soil organic matter dynamics. In: Driven by Nature: Plant Litter Quality and Decomposition, eds. G. Cadisch & K. E. Giller, pp. 316–336. UK: CAB International

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M. and Woomer, P.L. (1997b), Agricultural soils as a sink to mitigate CO2 emissions. Soil Use and Management, 13: 230-244. <https://doi.org/10.1111/j.1475-2743.1997.tb00594.x>

Thiagarajan, A., Fan, J., McConkey, B.G., Janzen, H.H., Campbell, C.A., 2018. Dry matter partitioning and residue N content for 11 major Canadian ﬁeld crops adjusted for rooting depth and yield. Can. J. Soil Sci. 98, 574–579. https://doi.org/10.1139/cjss-2017-0144

**2.3 Shelterbelt**

Amychev, B.Y., M.J. Bentham, S.N. Kulshreshtha, C.P. Laroque, J.M. Piwowar, and K.C.J. Van Rees. 2017. Carbon sequestration and growth of six common tree and shrub shelterbelts in Saskatchewan, Canada. Can. J. Soil Sci. 97: 368–381.

Andrén, O. and T. Kätterer. 1997. ICBM: The Introductory Carbon Balance Model for exploration of soil carbon balances. Ecological Applications 74: 1226-1236.

Bolinder, M.A., H.H. Janzen, E.G. Gregorich, D.A. Angers, & A.J.VandenBygaart. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems and Environment 118: 29-42.

Bolinder, M.A., O. Andrén, T. Kätterer, & L.E. Parent. 2008. Soil organic carbon sequestration potential for Canadian Agricultural Ecoregions calculated using the Introductory Carbon Balance Model. Canadian Journal of Soil Science 88: 451-460.

Gan, Y.T., C.A. Campbell, H.H. Janzen, R.L. Lemke, P. Basnyat, & C.L. McDonald. 2009. Carbon input to soil from oilseed and pulse crops on the Canadian prairies. Agriculture, Ecosystems and Environment 132: 290-297.

Janzen, H.H., K.A. Beauchemin, Y. Bruinsma, C.A. Campbell, R.L. Desjardins, B. H. Ellert and E.G. Smith. 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems 67: 85-102.

Kätterer, T. and O. Andrén. 1999. Long-term agricultural field experiments in Northern Europe: analysis of the influence of management on soil carbon stocks using the ICBM model. Agriculture, Ecosystems and Environment 72: 165-179.

Kätterer, T., L. Andersson, O. Andrén, and J. Persson. 2008. Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm. Nutrient Cycling in Agroecosystems 81: 145-155.

Kröbel, R., M.A. Bolinder, H.H. Janzen, S.M. Little, A.J. Vandenbygaart, and T. Kätterer. 2016. Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM). Agricultural Systems 143: 76–85.

Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, et al. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. 220: 480–504.

Soil Landscapes of Canada Working Group, 2010. Soil Landscapes of Canada version 3.2. Agriculture and Agri-Food Canada. (digital map and database at 1:1 million scale)

Website: <http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html>

**2.4 Water budget model**

Martel, M., Glenn, A., Wilsopn, H., Danielescu, S., Kröbel, R., Smith, W., McConkey, B., Guest, G., and Janzen, H., 2021. A parsimonious water budget model for Canadian agricultural conditions. Journal of Hydrology: Regional Studies 36, August 2021, 100846. <https://doi.org/10.1016/j.ejrh.2021.100846>

**2.5 N2O emission factor calculation (IPCC Tier 2)**

Bouwman, A.F., Boumans, L.J.M., and Batjes, N.H., 2002. Estimation of global NH3 volatilization loss from synthetic fertilizersand animal manure applied to arable lands and grasslands. GLOBAL BIOGEOCHEMICAL CYCLES,VOL.16,NO.2, 1024, <https://doi.org/10.1029/2000GB001389>

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

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/>

Liang, C., MacDonald, D., Thiagarajan, A., Flemming, C., Cerkowniak, D., and Desjardins, R., 2020. Developing a country specific method for estimating nitrous oxide emissions from agricultural soils in Canada. *Nutr Cycl Agroecosyst* **117,** 145–167. <https://doi.org/10.1007/s10705-020-10058-w>

Marshall, I.B., P Schut and M. Ballard (compilers). 1999. A National Ecological Framework for Canada: Attribute Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, Canada.

Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22: 205–223. <https://doi.org/10.1002/env.1044>

Pelster, D.E., Thiagarajan, A., Liang, B.C., Chantigny, M.H., Wagner-Riddle, C., Congreves, K.A., Lemke, R.L., Glenn, A., Tenuta, M., Hernandez-Ramirez, G., Bittman, S., Hunt, D., Owens, J., and MacDonald,, J.D., 2023. Ratio of non-growing season to growing season N2O emissions in Canadian croplands: an update to national inventory methodology. Canadian Journal of Soil Science (103). <https://doi.org/10.1139/cjss-2022-0101>.

Rochette, P., Liang, C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W.K., Flemming, C., 2018. Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables. Agriculture, Ecosystems & Environment 254, 69-81.

Rochette, P., D.E. Worth, R.L. Lemke, B.G. McConkey, D.J. Pennock, C. Wagner-Riddle and R.L. Desjardins. 2008. Estimation of N2O emissions from agricultural soils in Canada. I-Development of a country-specific methodology. Canadian Journal of Soil Science 88: 641−654.

**2.6 Multi-year N2O based on ICBM**

Bouwman, A.F., Boumans, L.J.M., and Batjes, N.H., 2002. Estimation of global NH3volatilization loss from synthetic fertilizersand animal manure applied to arable lands and grasslands. GLOBAL BIOGEOCHEMICAL CYCLES,VOL.16,NO.2, 1024, <https://doi.org/10.1029/2000GB001389>

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/>

Janzen, H.H., K.A. Beauchemin, Y. Bruinsma, C.A. Campbell, R.L. Desjardins, B.H. Ellert and E.G. Smith. 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems 67: 85-102.

Marshall, I.B., P Schut and M. Ballard (compilers). 1999. A National Ecological Framework for Canada: Attribute Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, Canada.

Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22: 205–223. <https://doi.org/10.1002/env.1044>

Rochette, P., D.E. Worth, R.L. Lemke, B.G. McConkey, D.J. Pennock, C. Wagner-Riddle and R.L. Desjardins. 2008. Estimation of N2O emissions from agricultural soils in Canada. I-Development of a country-specific methodology. Canadian Journal of Soil Science 88: 641−654.

Scheer, C., Fuchs., K., Pelster, D.E., and Butterbach-Bahl, K., 2020. Estimating global terrestrial denitrification from measured N2O:(N2O + N2) product ratios. Current Opinion in Environmental Sustainability 2020, 47:72–80. <https://doi.org/10.1016/j.cosust.2020.07.005>

**2.7 Multi-year N2O based on IPCC Tier 2 Carbon model**

Bouwman, A.F., Boumans, L.J.M., and Batjes, N.H., 2002. Estimation of global NH3volatilization loss from synthetic fertilizersand animal manure applied to arable lands and grasslands. GLOBAL BIOGEOCHEMICAL CYCLES,VOL.16,NO.2, 1024, <https://doi.org/10.1029/2000GB001389>

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/>

Janzen, H.H., K.A. Beauchemin, Y. Bruinsma, C.A. Campbell, R.L. Desjardins, B.H. Ellert and E.G. Smith. 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems 67: 85-102.

Marshall, I.B., P Schut and M. Ballard (compilers). 1999. A National Ecological Framework for Canada: Attribute Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, Canada.

Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22: 205–223. <https://doi.org/10.1002/env.1044>

Scheer, C., Fuchs., K., Pelster, D.E., and Butterbach-Bahl, K., 2020. Estimating global terrestrial denitrification from measured N2O:(N2O + N2) product ratios. Current Opinion in Environmental Sustainability 2020, 47:72–80. <https://doi.org/10.1016/j.cosust.2020.07.005>

**Table 4**

Statistics Canada, 2013a. Agricultural Water Use in Canada 2010. Published by authority of the Minister responsible for Statistics Canada, © Minister of Industry, 2013. October 2013, Catalogue no. 16-402-X, ISSN 1918-2910. Ottawa, ON, Canada. <https://www150.statcan.gc.ca/n1/en/pub/16-402-x/16-402-x2011001-eng.pdf?st=s-RIhfAz>

Statistics Canada, 2013b. Agricultural Water Use in Canada 2012. Published by authority of the Minister responsible for Statistics Canada, © Minister of Industry, 2013. December 2013, Catalogue no. 16-402-X, ISSN 1918-2910. Ottawa, ON, Canada. <https://www150.statcan.gc.ca/n1/en/pub/16-402-x/16-402-x2013001-eng.pdf?st=qMO66Z6z>

**Table 6**

Agriculture, Forestry and Rural Economic Development. 2020. Agricultural Operation Practices Act. Available at: <https://open.alberta.ca/publications/a07>

Ackerman, J., Khafipour, E., Cicek, N. 2018. Sustainable Re-Use of Dairy Cow Manure as Bedding and Compost: Nutrients and Self-Heating Potential. Canadian Biosystems Engineering / Le Genie des biosystems au Canada. 60:6.1-6.7. <https://doi.org/10.7451/CBE.2018.60.6.1>

Baldé, H., VanderZaag, A.C., Burtt, S.D., Wagner-Riddle, C., Evans, L., Gordon, R., Desjardins, R.L., MacDonald, J.D. 2018. Ammonia emissions from liquid manure storages are affected by anaerobic digestion and solid-liquid separation. Agricultural and Forest Meteorology 258: 80-88. <https://doi.org/10.1016/j.agrformet.2018.01.036>

Brown, C. 2013. Available Nutrients and Value for Manure From Various Livestock Types. Ontario Ministry for Food and Rural Affairs. Available at: <http://www.omafra.gov.on.ca/english/crops/facts/13-043.htm>

Cambareri, G., Wagner-Riddle, C., Drury, C., Lauzon, J., Salas, W. 2017. Anaerobically digested dairy manure as an alternative nitrogen source to mitigate nitrous oxide emissions in fall-fertilized corn. Canadian Journal of Soil Science. 97: 439–451. <https://doi.org/10.1139/CJSS-2016-0097>

Coppi, L. 2012. Nitrogen and phosphorus in soil and groundwater following repeated nitrogen-based swine slurry applications to a tame grassland on coarse textured soil. Unpublished PhD Thesis, University of Manitoba. Available at: <https://mspace.lib.umanitoba.ca/handle/1993/14417>

Dalby, F.R., Hafner, S.D., Petersen, S.O., VanderZaag, A.C., Habtewold, J., Dunfield, K., Chantigny, M.H., Sommer, S.G. 2021. Understanding methane emission from stored animal manure: A review to guide model development. Journal of Environmental Quality. 50: 817-835. <https://doi.org/10.1002/jeq2.20252>

Dick, S. 2003. Fluctuations in manure nutrient concentration during swine storage pump-outs. Final Report for the Manitoba Livestock Manure Management Initiative. MLMMI 03-01-06. Available at: <https://agra-gold.ca/wp-content/uploads/2021/06/MLMMI-Project-03-01-06.pdf>

ECCC, 2021. National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC8369. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>.

Evans, L., VanderZaag, A.C., Sokolov, V., Baldé, H., MacDonald, D., Wagner-Riddle, C., Gordon, R. 2018. Ammonia emissions from the field application of liquid dairy manure after anaerobic digestion or mechanical separation in Ontario, Canada. Agricultural and Forest Meteorology. 258: 89–95. <https://doi.org/10.1016/j.agrformet.2018.02.017>

Farrow, C. 2016. Anaerobic digestion of poultry manure: Implementation of ammonia control to optimize biogas yield. Unpublished PhD Thesis, University of Guelph, ON, Canada.

Fillingham, M.A., VanderZaag, A.C., Burtt, S., Baldé, H., Ngwabie, N.M., Smith, W., Hakami, A., Wagner-Riddle, C., Bittman, S., MacDonald, D. 2017. Greenhouse gas and ammonia emissions from production of compost bedding on a dairy farm. Waste Management.70: 45-52. <https://doi.org/10.1016/j.wasman.2017.09.013>

Fitzgerald, M.M. and Racz, G.J. 2001. Long-term effect of hog manure on soil quality and productivity. Volume 1: properties and composition of Hog manure samples. Final report for the Agri-Food Research and Development Initiative. Available at: <http://manure.mb.ca/projects/pdfs/Racz%20and%20Fitzgerald%20Volume%201%20-%20Properties.pdf>

Fraser, H.W. 2020. Manure storages for small- to medium-sized horse farms.Available at: <https://files.ontario.ca/omafra-manure-storages-for-horse-farms-20-047-en-23-06-20.pdf>

Government of Alberta 2013. Manure Characteristics and Land Base Code. Available at: <https://open.alberta.ca/publications/6921902>.

Government of Alberta 2021. Manure application. Available at: <https://www.alberta.ca/manure-application.aspx>

Government of Manitoba 2009. Manure Management Facts: Calculating Manure Application Rates. Available at: <https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/mmf_calcmanureapprates_factsheet.pdf>

Government of Manitoba 2015. Properties of Manure. Available at: <https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/properties-of-manure.pdf>

Hao, X., Chang, C., Larney, F.J., Travis, G.R. 2001. Greenhouse Gas Emissions during Cattle Feedlot Manure Composting. Journal of Environmental Quality. 30: 376-386. <https://doi.org/10.2134/jeq2001.302376x>

Hao, X., Chang, C., Larney, F.J. 2004. Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting. Journal of Environmental Quality. 33: 37-44. <https://doi.org/10.2134/jeq2004.3700>

Hao, X., Benke, M.B., Gibb, D.J., Stronks, A., Travis, G., McAllister, T.A. 2009. Effects of Dried Distillers’ Grains with Solubles (Wheat-Based) in Feedlot Cattle Diets on Feces and Manure Composition. Journal of Environmental Quality. 38: 1709-1718. <https://doi.org/10.2134/jeq2001.302376x>

Hao, X., Hill, B., Caffyn, P., Travis, G., Olson, A.F., Larney, F.J., McAllister, T.A., Alexander, T. 2014. Co-composting of beef cattle feedlot manure with construction and demolition waste. Journal of Environmental Quality. 43: 1799-1808. <https://doi.org/10.2134/jeq2014.02.0087>

Helgason, B.L., H.H. Janzen, D.A. Angers, M. Boehm, M. Bolinder, R.L. Desjardins, J. Dyer, B.H. Ellert, D.J. Gibb, E.G. Gregorich, R. Lemke, D. Massé, S.M. McGinn, T.A. McAllister, N. Newlands, E. Pattey, P. Rochette, W. Smith, A.J. VandenBygaart and H. Wang. 2005. GHGFarm: An assessment tool for estimating net greenhouse gas emissions from Canadian farms. Agriculture and Agri-Food Canada, Ottawa, ON, Canada.

Hilborn, V. 2011. Anaerobic digestion of broiler chicken manure. Unpublished Masters Thesis, University of Guelph, ON, Canada.

Hofmann, N. and Beaulieu, M.S., 2006. A Geographical Profile of Manure Production in Canada, 2001. Statistics Canada Agriculture Division, Agriculture and Rural Working Paper Series. Published by authority of the Minister responsible for Statistics Canada, © Minister of Industry, 2006. Catalogue no. 21-601-MIE, ISSN 1707-0368, ISBN 0-662-42478-6, Ottawa, ON, Canada. <https://www150.statcan.gc.ca/n1/en/pub/21-601-m/21-601-m2006077-eng.pdf?st=9mxp6ymp>

Johannesson, G.H., Lauzon, J., Crolla, A., Gilroyed, B., VanderZaag, A., Gordon, R. 2018. Impact of manure storage conditions and time on decomposition of and losses from liquid dairy manure stored in a temperate climate. Canadian Journal of Soil Science. 98: 148-160. <https://doi.org/10.1139/cjss-2017-0083>

Kariyapperuma, K.A., Johannesson, G., Maldaner, L., VanderZaag, A., Gordon, R., Wagner-Riddle, C. 2018a. Year-round methane emissions from liquid dairy manure in a cold climate reveal hysteretic pattern. Agricultural and Forest Meteorology. 258: 56–65. <https://doi.org/10.1016/j.agrformet.2017.12.185>

Kariyapperuma, K., Wagner-Riddle, C., Duke, C. 2018b. Assessing manure and digestate fertilizers: environmental benefits and nutrient management practices from barn to field. BMPVD 2015-2826 Final Report – Draft. pp 45.

Larney, F.J., Olson, A.F., Miller, J.J., DeMaere, P.R., Zvomuya, F., McAllister, T.A. 2008. Physical and Chemical Changes during Composting of Wood Chip–Bedded and Straw-Bedded beef Cattle Feedlot Manure. Journal of Environmental Quality 37: 725-735. <https://doi.org/10.2134/jeq2007.0351>

Larney, F.J., Olson, A.F., Miller, J.J., Tovell, B.C. 2014. Nitrogen and Phosphorus in Runoff from Cattle Manure Compost Windrows of Different Maturities. Journal of Environmental Quality. 43: 671-680. <https://doi.org/10.2134/jeq2013.06.0230>

Larney, F.J. and Olson, A.F. 2006. Windrow temperatures and chemical properties during active and passive aeration composting of beef cattle feedlot manure. Canadian Journal of Soil Science 86: 783-797. <https://doi.org/10.4141/S06-031>

Larney, F.J., Buckley, K.E., Hao, X., McCaughey, W.P. 2006. Fresh, Stockpiled, and Composted beef Cattle Feedlot Manure: Nutrient Levels and Mass Balance Estimates in Alberta and Manitoba. Journal of Environmental Quality. 35: 1844-1854. <https://doi.org/10.2134/jeq2005.0440>

LeRiche, E.L., VanderZaag, A.C., Wood, J.D., Wagner-Riddle, C., Dunfield, K., Ngwabie N.M., McCabe, J., Gordon, R.J. 2016. Greenhouse Gas Emissions from Stored Dairy Slurry from Multiple Farms. Journal of Environmental Quality. 45: 1822-1828. <https://doi.org/10.2134/jeq2016.04.0122>

Lorimor, J., Powers, W., Sutton, A. 2004. Manure Characteristics: Manure Management Systems Series. MWPS-18 Section 1. Second Edition. Available at: <https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf>

Loro, P. 2005. Characterization of Solid Beef Manure. Report prepared for The Manitoba Cattle Producers Association, Manitoba Agriculture, Food and Rural Initiatives. Available at: <https://www.gov.mb.ca/agriculture/livestock/beef/pubs/characterization-of-solid-beef-manure.pdf>.

Maldaner, L., Wagner-Riddle, C., VanderZaag, A.C., Gordon, R., Duke, C. 2018. Methane emissions from storage of digestate at a dairy manure biogas facility. Agricultural and Forest Meteorology. 258: 96–107. <https://doi.org/10.1016/j.agrformet.2017.12.184>

Manitoba Agriculture, Food and Rural Development. 2015. Properties of Manure. Available at: <https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/properties-of-manure.pdf>

Miller, J.J., Beasley, B.W., Yanke, L.J., Larney, F.J., McAllister, T.A., Olson, B.M., Selinger, L.B., Chanasyk, D.S., Hasselback, P. 2003. Bedding and seasonal effects on chemical and bacterial properties of feedlot cattle manure. Journal of Environmental Quality. 32: 1887-1894. <https://doi.org/10.2134/jeq2003.1-887>

Miller, J.J., Beasley, B.W., Larney, F.J., Olson, B.M. 2004. Barley dry matter yield, crop uptake, and soil nutrients under fresh and composted manure containing straw or wood-chip bedding. Canadian Journal of Plant Science. 84: 987-999. <https://doi.org/10.4141/P03-208>

Miller, J.J., Beasley, B.W., Drury, C.F., Zebarth, B.J. 2009. Barley Yield and Nutrient Uptake for Soil Amended with Fresh and Composted Cattle Manure. Agronomy Journal. 101: 1047-1059. <https://doi.org/10.2134/agronj2009.0057>

Nennich, T.D., Harrison, J.H., VanWieringen, L.M., Meyer, D., Heinrichs, A.J., Weiss, W.P., St-Pierre, N.R., Kincaid, R.L., Davidson, D.L., Block, E. 2005. Prediction of manure and nutrient excretion from dairy cattle. Journal of Dairy Science. 88: 3721-3733. <https://doi.org/10.3168/jds.S0022-0302(05)73058-7>

Ngwabie, N.M., Gordon, R.J., VanderZaag, A., Dunfield, K., Sissoko, A., Wagner-Riddle, C. 2016. The Extent of Manure Removal from Storages and Its Impact on Gaseous Emissions. Journal of Environmental Quality. 45:2023–2029. <https://doi.org/10.2134/jeq2016.01.0004>

NRCC 1983. Farm animal manures in the Canadian environment. Prepared for the Management Subcommittee, NRC Associate Committee on Scientific Criteria for Environmental Quality. National Research Council of Canada Available at: https://atrium.lib.uoguelph.ca/xmlui/handle/10214/15108

Olson, B.M. and Papworth, L.W. 2002. Manure application on forages. Alberta Agriculture, Food and Rural Development, Lethbridge, Alberta, Canada. Final report for the Canada-Alberta Beef Industry Development Fund and the Canada-Alberta Hog Industry Development Fund. 257 pp. Available at: <https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/irr15479/$FILE/manure_on_forages.pdf>.

Park, K.-H., Ngwabie, N.M., Wagner-Riddle, C. 2014. Chamber measurement methods and aeration effect on greenhouse gas fluxes during composting. Agricultural Engineering Journal: CIGR Journal 16: 32-44. <https://cigrjournal.org/index.php/Ejounral/article/view/2467>

Pattey, E., Trzcinski, M.K., Desjardins, R.L. 2005 Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. Nutrient Cycling in Agroecosystems. 72: 173-187. <https://doi.org/10.1007/s10705-005-1268-5>

Paul, J.W. and Beauchamp, E.G. 1989. Effect of carbon constituents in manure on denitrification in soil. Canadian Journal of Soil Science. 69: 49-61. <https://doi.org/10.4141/cjss89-006>

Paul, J.W. and Beauchamp, E.G. 1993. Nitrogen availability for corn in soils amended with urea' cattle slurry, and solid and composted manures. Canadian Journal of Soil Science. 73: 253-266. <https://doi.org/10.4141/cjss93-027>

Paul, J.W. and Beauchamp, E.G. 1994. Short-term nitrogen dynamics in soil amended with fresh and composted cattle manures. Canadian Journal of Soil Science. 74: 147-155. <https://doi.org/10.4141/cjss94-022>

The Prairie Provinces’ Committee on Livestock Development and Manure Management 2006a. Tri-provincial manure application and use guidelines (Manitoba Version). Available at: <https://www.gov.mb.ca/agriculture/crops/guides-and-publications/pubs/manure-application-and-use-guidelines.pdf>

The Prairie Provinces’ Committee on Livestock Development and Manure Management 2006b. Tri-provincial -manure application and use guidelines (Saskatchewan Version). Available at: <http://www.gov.pe.ca/photos/original/af_NM_manconv.pdf>

Sommer, S.G., McGinn, S.M., Hao, X., Larney, F.J. 2004. Techniques for measuring gas emissions from a composting stockpile of cattle manure. Atmospheric Environment. 38: 4643-4652. <https://doi.org/10.1016/j.atmosenv.2004.05.014>

Sukler, S.M., Lewis, D., Robinson, C., McConville, N. 2015. British Columbia Manure and Crop Nutrients. A Review of Current Data and Regional Fieldwork focused on Southwest British Columbia. Prepared for: British Columbia Ministry of Agriculture. Available at: <https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/nutrient-management/bc_manure_and_crop_nutrients_report.pdf>.

Stefankiw, J. 2012. Novel organic amendments to improve soil fertility and plant nutrition. Unpublished Masters Thesis, University of Saskatchewan. Available at: <https://harvest.usask.ca/handle/10388/ETD-2012-05-456>

Tenuta, M., Coppi, L., Ackerman, J. 2013. Enhancing sustainability of grassland systems receiving pig manure on coarse texture soil. Project MLMMI 06-01-01: Final Report to the Manitoba Livestock and Manure Management Initiative, pp 44. Available at: <http://manure.mb.ca/projects/pdfs/Final%20Report%2006%2001%2001.pdf>

Thompson, A.G., Wagner-Riddle, C., Fleming, R. 2004. Emissions of N2O and CH4 during the composting of liquid swine manure. Environmental Monitoring and Assessment. 91: 87-104. <https://doi.org/10.1023/B:EMAS.0000009231.04123.2d>

VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W. 2009. Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. Transactions of the ASABE 599-608. <https://doi.org/10.13031/2013.26832>

VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W. 2010a. Permeable synthe: tic covers for controlling emissions from liquid dairy manure. Applied Engineering in Agriculture. 26: 287‐297. <https://doi.org/10.13031/2013.29544>

VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., Stratton, G.W. 2010b. Effects of winter storage conditions and subsequent agitation on gaseous emissions from liquid dairy manure. Canadian Journal of Soil Science. 90: 229-239. <https://doi.org/10.4141/CJSS09040>

VanderZaag, A.C., Baldé, H., Habtewold, J., Le Riche, E.L., Burtt, S., Dunfield, K., Gordon, R.J., Jenson, E., Desjardin, R.L. 2019. Intermittent Agitation of Liquid Manure: Effects on Methane, Microbial Activity, and Temperature in a Farm-Scale Study. Journal of the Air and Waste Management Association. 69: 1096-1106. <https://doi.org/10.1080/10962247.2019.1629359>

VanderZaag, A.C., Glenn, A., Balde, H. 2021. Manure methane emissions over three years at a swine farm in western Canada. Journal of Environmental Quality. 51: 301-311. <https://doi.org/10.1002/jeq2.20336>

Wedwitschka, H., Hayes, A., Gallegos Ibanez, D., Jenson, E., Liebtrau, J., Nelles, M., Stinner, W. 2022. Material characterization and conditioning of cattle feedlot manure as feedstock for dry batch anaerobic digestion. Waste Management. 138: 210-218. <https://doi.org/10.1016/j.wasman.2021.11.047>

Whalen, J.K., Chang, C., Clayton, G.W. 2002. Cattle manure and lime amendments to improve crop production of acidic soils in northern Alberta. Canadian Journal of Soil Science. 82: 227-238. <https://doi.org/10.4141/S01-030>

Zvomuya, F., Helgason, B.L., Larney, F.J., Janzen, H.H., Akinremi, O.O., Olson, B.M. 2006. Predicting Phosphorus Availability from Soil-Applied Composted and Non-Composted Cattle Feedlot Manure. Journal of Environmental Quality. 35:928–937. <https://doi.org/10.2134/jeq2005.0409>

**Table 7**

Austin, E., Wickings, K., McDaniel, M., Robertson, G., and Grandy, A., 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. GCB Bioenergy, 9, 1252-1263. <https://doi.org/10.1111/gcbb.12428>

Bender, A., Tamm, S., and Aavola, R., 2017. Biomass allocation to shoots and roots, and nutrient content in herbage legumes. Grassland Science in Europe: Grassland resourses for extensive farming systems in marginal lands: major drivers and future scenarios. Alghero, Italy 7-10 May 2017. Ed. C. Porgueddu, A. Franca, G. Lombardi, G. Molle, G. Peratoner, A. Hopkins. Wageningen: Wageningen Academic Publishers, 521−523. (Volume 22).

Bergstrom, L., and Jokela, W., 2001. Ryegrass cover crop effects on nitrate leaching in spring barley fertilized with 15NH415NO3. Journal of Environmental Quality, 30, 1659-1667. <https://doi.org/10.2134/jeq2001.3051659x>

Berrocal-Ibarra, S., Ortiz,Cereceres, J., and Pena-Valdivia, C.B., 2002. Yield components, harvest index and leaf area efficiency of a sample of a wild population and a domesticated variant of the common bean Phaseolus vulgaris. South African Journal of Botany 68 (2), 205-211. <https://doi.org/10.1016/S0254-6299(15)30421-X>

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., and Vandenbygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems & Environment 118 (1–4), 29-42. <https://doi.org/10.1016/j.agee.2006.05.013>

Bolinder, M.A., Kätterer, T., Poeplau, C., Börjesson, G., and Parent, L.E., 2015. Net primary productivity and below-ground crop residue inputs for root crops: Potato (Solanum tuberosum L.) and sugar beet (Beta vulgaris L.). Canadian Journal of Soil Science. 95(2): 87-93. <https://doi.org/10.4141/cjss-2014-091>

Cogliatti, M., Bongiorno, F., Dalla Valle, H., and Rogers, W.J., 2011. Canaryseed (Phalaris canariensis L.) accessions from nineteen countries show useful genetic variation for agronomic traits. Canadian Journal of Plant Science. 91(1): 37-48. <https://doi.org/10.4141/cjps09194>

Creamer, N., and Baldwin, K., 2000. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortScience, 35, 600-603. <https://doi.org/10.21273/HORTSCI.35.4.600>

Dietzel, R., 2014. A comparison of carbon storage potential in corn- and prairie-based agroecosystems. Dissertation, Agronomy Department, Iowa State University. Ames, IA. <https://doi.org/10.31274/etd-180810-3221>

Fang, Y.Y., Pal Signh, B., Badgery, W., and He, X.H., 2016. In situ assessment of new carbon and nitrogen assimilation and allocation in contrastingly managed dryland wheat crop–soil systems. Agriculture, Ecosystems & Environment 235, 80-90. <https://doi.org/10.1016/j.agee.2016.10.010>

Field Crop News (2021) Moisture Content and the Hay Drying Curve. <https://fieldcropnews.com/2021/06/moisture-content-and-the-hay-drying-curve/>.

Francis, G., Bartley, K., and Tabley, F., 1998. The effect of winter cover crop management on nitrate leaching losses and crop growth. Journal of Agricultural Science, 131, 299-308. <http://dx.doi.org/10.1017/S0021859698005899>

Franzluebbers, K., Weaver, R.W., Juo, A.S.R., and Franzluebbers, A.J., 1994. Carbon and nitrogen mineralization from cowpea plants part decomposing in moist and in repeatedly dried and wetted soil. Soil Biology and Biochemistry, 26, 1379-1387. <https://doi.org/10.1016/0038-0717(94)90221-6>

Gan, Y.T., Campbell, C.A., Janzen, H.H., Lemke, R.L., Basyat, P., and McDonald, C.L., 2009. Carbon input to soil from oilseed and pulse crops on the Canadian prairies. Agriculture, Ecosystems & Environment 132 (3–4), 290-297. <https://doi.org/10.1016/j.agee.2009.04.014>

Gan Y.T., Liang B.C., Liu L.P., Wang X.Y., and McDonald C. L., 2011. C : N ratios and carbon distribution profile across rooting zones in oilseed and pulse crops. Crop and Pasture Science 62, 496-503. <https://doi.org/10.1071/CP10360>

Ghimire, R., Norton, J.B., & Pendall, E., 2014 Alfalfa-grass biomass, soil organic carbon, and total nitrogen under different management approaches in an irrigated agroecosystem. Plant Soil 374, 173–184 (2014). <https://doi.org/10.1007/s11104-013-1854-2>

Government of Ontario (2024) Understanding pasture gains in a wet weather year. <https://www.ontario.ca/page/understanding-pasture-gains-wet-weather-year>

Hakala, K., Keskitalo, M., and Erikson, C., 2009. Nutrient uptake and biomass accumulation for eleven different field crops. Agricultural and Food Science 18 (3-4), 366–387. <https://doi.org/10.23986/afsci.5947>

Janzen, H.H., Beauchemin, K.A., Bruinsma, Y., Campbell, C.A., Desjardins, R.L., Ellert, B.H., and Smith, E.G., 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems volume 67, pages 85–102. <https://doi.org/10.1023/A:1025195826663>

Jucá Taveira, C., Farrell, R.E., Wagner-Riddle, C., Machado, P.V.F., Deen, B., and Congreves, K.A., 2020. Tracing crop residue N into subsequent crops: Insight from long-term crop rotations that vary in diversity. Field Crops Research 255, 107904, ISSN 0378-4290, <https://doi.org/10.1016/j.fcr.2020.107904>

Kaspar, T., Jaynes, D., Parkin, T., Moorman, T., and Singer, J., 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agriculture Water Management, 110, 25-33. <https://doi.org/10.1016/j.agwat.2012.03.010>

Kuo, S., Sainju, U.M., and Jellum, E.J., 1997. Winter cover cropping influence on nitrogen in soil. Soil Science Society of America Journal, 61, 1392–1399. <https://doi.org/10.2136/sssaj1997.03615995006100050016x>

Lawley, Y.E., Weil, R.R., and Teasdale, J.R., 2011. Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agromony Journal, 103, 137-144. <https://doi.org/10.2134/agronj2010.0187>

Lenzi, A., Antichi, D., Bigongiali, F., Mazzoncini, M., Migliorini, P., and Tesi, R., 2009. Effect of different cover crops on organic tomato production. Renewable Agriculture and Food System, 24, 92-101. <https://www.jstor.org/stable/44490608>

Little, S.M., Lindeman, J., Maclean, K., and Janzen, H.H., 2008. Holos - A tool to estimate and reduce GHGs from farms. Methodology and algorithms for Version 1.1.x. Agriculture & Agri-Food Canada, Ottawa, Ontario, 158 pages.

Luna, J.M., Sullivan, D.M., Garrett, A.M., and Xue, L., 2018. Cover crop nitrogen contribution to organic broccoli production. Renewable Agriculture and Food Systems, 35, 49-58. <http://dx.doi.org/10.1017/S1742170518000236>

Neilson J., 2019. Unpublished data. <https://profils-profiles.science.gc.ca/en/profile/jonathan-d-neilson?wbdisable=true>

MadBarn (2024) Hay Versus Pasture Grass for Horses: Comparing Forage Sources.

<https://madbarn.ca/hay-vs-pasture-grass-for-horses/#:~:text=Moisture%3A%20Pasture%20contains%20more%20water,C%2C%20and%20E%20than%20pasture>.

Mahmood, A., and Honermeier, B., 2012. Chemical composition and methane yield of sorghum cultivars with contrasting row spacing. Field Crops Research 128, 27–33. <https://doi.org/10.1016/j.fcr.2011.12.010>

Puget, P., and Drinkwater, L.E., 2001. Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure. Soil Science Society of America Journal, 65, 771-779. <https://doi.org/10.2136/sssaj2001.653771x>

Ramirez-Garcia, J., Gabriel, J.L., Alonso-Ayuso, M., and Quemada, M., 2015. Quantitative characterization of five cover crop species. Journal of Agricultural Sciences, 153, 1174-1185. <http://dx.doi.org/10.1017/S0021859614000811>

Ross, S.M., Izaurralde, R.C., Janzen, H.H., Robertson, J.A., and McGill, W.B., 2008. The nitrogen balance of three long-term agroecosystems on a boreal soil in western Canada, Agriculture, Ecosystems & Environment, Volume 127, Issues 3–4, Pages 241-250, ISSN 0167-8809, <https://doi.org/10.1016/j.agee.2008.04.007>

Sainju, U.M., Singh, B.P., and Whitehead, W.F., 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Canadian Journal of Soil Science, 80, 523-532. <https://doi.org/10.4141/S02-056>

Sainju, U.M., Whitehead, W.F. & Singh, B.P., 2005. Carbon accumulation in cotton, sorghum, and underlying soil as influenced by tillage, cover crops, and nitrogen fertilization. Plant Soil 273, 219–234. <https://doi.org/10.1007/s11104-004-7611-9>

Santos, N.Z.D., Dieckow, J., Bayer, C., Molin, R., Favaretto, N., Pauletti, V., and Piva, J.T., 2011. Forages, cover crops and related shoot and root additions in no-till rotations to C sequestration in a subtropical Ferralsol. Soil and Tillage Research, 111, 208–218. <https://doi.org/10.1016/j.still.2010.10.006>

Soon, Y.K., and Lupwayi, N.Z., 2012. Straw management in a cold semi-arid region: Impact on soil quality and crop productivity. Field Crops Research, 139 39-46. <http://dx.doi.org/10.1016/j.fcr.2012.10.010>

Thiessen Martens, J.R., Lynch, D.H., and Entz, M.H., 2019. A survey of green manure productivity on dryland organic grain farms in the eastern prairie region of Canada. Canadian Journal of Plant Science, 99, 772-776. <https://doi.org/10.1139/cjps-2018-0311>

Toom, M., Talgre, L., Mäe, A., Tamm, S., Narits, L., Edesi, L., Haljak, M., and Lauringson, E., 2019. Selecting winter cover crop species for northern climatic conditions. Biological Agriculture & Horticulture, 35, 263-274. <https://doi.org/10.1080/01448765.2019.1627908>

Vaillancourt, M., Chantigny, M., Pageau, D., and Vanasse, A., 2018. Impact of a clover cover crop combined with organic or mineral fertilizer on yield and nitrogen uptake of canola. Can. J. Plant Sci. 98: 332 - 344. <https://doi.org/10.1139/cjps-2017-0180>

Wang, F., Weil, R.R., Han, L., Zhang, M., Sun, Z., and Nan, X., 2018. Subsequent nitrogen utilization and soil water distribution is affected by forage radish cover crop and nitrogen fertilizer in a corn silage production system. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 69, 52-61. <https://doi.org/10.1080/09064710.2018.1498911>

Yang, X., Drury, C., Reynolds, W., and Reeb, M., 2019. Legume Cover Crops Provide Nitrogen to Corn During a Three‐Year Transition to Organic Cropping. Agron. J., 111: 3253-3264. <https://doi.org/10.2134/agronj2018.10.0652>

Yang, X.M., Drury, C.F., Reynolds, W.D., and Phillips, L.A., 2020. Nitrogen release from shoots and roots of crimson clover, hairy vetch, and red clover. Can. J. Soil Sci. 100: 179–188. <https://doi.org/10.1139/cjss-2019-0164>

**Table 8**

Campbell, C. A. & Zentner, R. P. (1997) Crop production and soil organic matter in long-term crop rotations in the Semi-Arid Northern Great Plains of Canada. In: Soil Organic Matter in Temperate Agroecosystems, eds. E. A. Paul, E. T. Elliott, K. Paustian & C. V. Cole, pp. 317-333. Boca Raton: CRC Press.

Collins, H. P., Elliott, E. T., Paustian, K., Bundy, L. G., Dick, W. A., Huggins, D. R., Smucker, A. J. M. & Paul, E. A. (2000) Soil carbon pools and fluxes in long-term Corn Belt agroecosystems. Soil Biology and Biochemistry32(2): 157-168.

Dick, W. A., Edwards, W. M. & McCoy, E. L. (1997) Continuous application of no-tillage to Ohio soils: Changes in crop yields and organic matter-related soil properties. In: Soil Organic Matter in Temperate Agroecosystems, eds. P. E.A., K. Paustian, E. T. Elliott & C. V. Cole, Boca Raton, FL, USA: CRC Press, Inc.

Díaz-Zorita, M., Barraco, M. & Alvarez, C. (2004) Effects of twelve years of tillage practices on an Hapludoll from the Northwetern of Buenos Aires Province, Argentina. Ciencia del Suelo 22: 11-18.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F. & Cohan, J. (2014) Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agriculture Ecosystem & Environment 188: 134-146.

e-RA. (2013) The electronic Rothamsted Archive. In.

Gregorich, E. G., Ellert, B. H., Drury, C. F. & Liang, B. C. (1996) Fertilization effects on soil organic matter turnover and corn residue C storage. Soil Science Society of America Journal 60: 472-476.

Halvorson, A. D., Vigil, M. F., Peterson, G. A. & Elliott, E. T. (1997) Long-term tillage and crop residue management study at Akron, Colorado. Boca Raton, FL: CRC PRESS.

Huggins, D. R. & Fuchs, D. J. (1997) Long-term N management effects on corn yield and soil C of an aquic haplustoll in Minnesota. In Soil Organic Matter In Temperate Agroecosystems. In: Soil Organic Matter in Temperate Agroecosystems, eds. E. A. Paul, E. T. Elliott, K. Paustian & C. V. Cole, pp. 317-333. Boca Raton: CRC Press.

Janzen, H. H., Johnston, A. M., Carefoot, J. M. & Lindwall, C. W. (1997) Soil organic matter dynamics in long-term experiments in southern Alberta. In: Soil Organic Matter in Temperate Agroecosystems, eds. E. A. Paul, E. T. Elliott, K. Paustian & C. V. Cole, pp. 317-333. Boca Raton: CRC Press.

Jenkinson, D. S. (1990) The turnover of organic carbon and nitrogen in soil. Philosophical Transactions of the Royal Society B: Biological Sciences 329: 361-368.

Jenkinson, D. S. & Johnston, A. E. (1977) Soil organic matter in the Hoosefield Continuous Barley Experiment. In: Report for 1976, Part 2, pp. 87-101.

LTER, K. (2017) Kellogg Biological Station. Long-Term Ecological Research Data Catalog. In: https://lter.kbs.msu.edu/data/: Kellogg Biological Station, Michigan State University.

Küstermann, B., Munch, J. C. & Hülsbergen, K. J. (2013) Effects of soil tillage and fertilization on resource efficiency and greenhouse gas emissions in a long-term field experiment in Southern Germany. European Journal of Agronomy 49: 61-73.

Maillard, É., McConkey, B. G., St. Luce, M., Angers, D. A. & Fan, J. (2018) Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada. Soil and Tillage Research 177: 97-104.

Marchado 2013 – *IPCC 2019 has no such reference, and it could not be located by search either*

Machado, S. (2011) Soil organic carbon dynamics in the Pendleton long-term experiment: Implications of biofuel production in Pacific Northwest. Agronomy Journal 103: 253-260.

Machado, S., Petrie, S., Rhinhart, K. & Ramig, R. E. (2008) Tillage effects on water use and grain yield of winter wheat and green pea in rotation. Agronomy Journal 100(1): 154-162.

Pierce, F. J. & Fortin, M. C. (1997) Long-term tillage and periodic plowing of a no-tilled soil in Michigan: Impacts, yield, and soil organic matter. Boca Raton, FL, USA: CRC Press Inc.

Rasmussen, P. E. & Smiley, R. W. (1997) Soil carbon and nitrogen change in long-term agricultural experiments at Pendleton, Oregon. In: Soil Organic Matter in Temperate Agroecosystems, eds. E. A. Paul, E. T. Elliott, K. Paustian & C. V. Cole, pp. 317-333. Boca Raton: CRC Press.

Schultz, J. E. (1995) Crop production in a rotation trial at Tarlee, South Australia. Australian Journal of Experimental Agriculture 35: 865-876.

Skjemstad, J. O., Spouncer, L. R., Cowie, B. & Swift, R. S. (2004) Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. Australian Journal of Soil Research 42(1): 79-88.

Vanotti, M. B., Bundy, L. G. & Peterson, A. E. (1997) Nitrogen fertilizer and legume-cereal rotation effects on soil production and organic matter dynamics in Wisconsin. In: Soil Organic Matter in Temperate Agroecosystems, eds. E. A. Paul, E. T. Elliott, K. Paustian & C. V. Cole, pp. 317-333. Boca Raton: CRC Press.

**Table 9**

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/>

Equi-Analytical Laboratories 2018 - Laboratories, E.-A. (2018) Interactive common feed profiles. In: https://equi-analytical.com/interactive-common-feed-profile/: Equi-Analytical Laboratories.

Cornell University (2017) - University, C. (2017) Substrate composition table. In: http://compost.css.cornell.edu/lignin.table.html: Cornell Composting. Cornell Waste Management Institute, Cornell University.

Zereu, G., Negesse, T. & Nurfeta, A. (2014) Chemical composiiton and in vitro dry matter digestibility of vines and roots of four sweet potato (Ipomoea batatas) varieties grown in southern Ethiopia. Tropical and Subtropical Agroecosystems 17: 547-555.

**Table 10**

ASABE. 2005. Manure production and characteristics. D384.2. American Society of Agricultural and Biological Engineers, St. Joseph, MI. Available at: <https://elibrary.asabe.org/abstract.asp?aid=32018>

Chen, S., Liao, W., Liu, C., Wen, Z., Kincaid, R.L., Harrison, J.H., Elliott, D.C., Brown, M.D., Solana, A.E., Stevens, D.J. 2003. Value-added chemicals from animal manure. PNNL-14495. Pacific Northwest National Lab., Richland, WA. US Department of Energy. Available at: <https://doi.org/10.2172/15009485>

Hébert, M., Karam, A., Parent, L.E. 1991. Mineralization of nitrogen and carbon in soils amended with composted manure. Biological Agriculture and Horticulture. 7(4): 349-361. <https://doi.org/10.1080/01448765.1991.9754565>

Lorimor, J., Powers, W., Sutton, A. 2004. Manure Characteristics: Manure Management Systems Series. MWPS-18 Section 1. Second Edition. Available at: <https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf>

Rees, R. and Castle, K. 2002. Nitrogen recovery in soils amended with organic manures combined with inorganic fertilisers. Agronomie. 22: 739-746. <https://doi.org/10.1051/agro:2002061>

Sørensen, P. and Jensen, E.S. 1995. Mineralization of carbon and nitrogen from fresh and anaerobically stored sheep manure in soils of different texture. Biology and Fertility of Soils. 19: 29-35. <https://doi.org/10.1007/BF00336343>

**Table 11**

Amichev, B.Y., M.J. Bentham, S.N. Kulshreshtha, C.P. Laroque, J.M. Piwowar, and K.C.J. Van Rees. 2017. Carbon sequestration and growth of six common tree and shrub shelterbelts in Saskatchewan, Canada. Can. J. Soil Sci. 97: 368–381.

**Table 13**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

Liang, C., MacDonald, D., Thiagarajan, A., Flemming, C., Cerkowniak, D., and Desjardins, R., 2020. Developing a country specific method for estimating nitrous oxide emissions from agricultural soils in Canada. *Nutr Cycl Agroecosyst* **117,** 145–167. https://doi.org/10.1007/s10705-020-10058-w

Rochette, P., Liang, C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W.K., Flemming, C., 2018. Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables. Agriculture, Ecosystems & Environment 254, 69-81.

Worth, D., 2022. Preliminary literature analysis of 4R nutrient practices on N2O emissions. Personal Communication. <https://opengovca.com/employee/devon-worth>

**Table 14**

Bouwman, A.F., Boumans, L.J.M., and Batjes, N.H., 2002. Estimation of global NH3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. GLOBAL BIOGEOCHEMICAL CYCLES,VOL.16,NO.2, 1024. <https://doi.org/10.1029/2000GB001389>

**Table 15**

Janzen, H., 2010. Personal communication. <https://opengovca.com/employee/henry-janzen>

**Table 48**

Brentrup, F., Lammel, J., Stephani, T., Christensen, B., 2018. Updated carbon footprint values for mineral fertilizer from different world regions. 11th International Conference on Life Cycle Assessment of Food 2018 (LCA Food) in conjunction with the 6th LCA AgriFood Asia and 7th International Conference on Green and Sustainable Innovation (ICGSI) on “Global food challenges towards sustainable consumption and production” 17-19 October 2018, Bangkok, Thailand <https://www.researchgate.net/publication/329774170_Updated_carbon_footprint_values_for_mineral_fertilizer_from_different_world_regions>

**Table 60**

Bailey, A.W., Mccartney, D., Schellenberg, M.P., 2010 Management of Canadian Prairie Rangeland. <https://publications.gc.ca/site/eng/433214/publication.html>

# 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)**

**Note:** 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 1990-2017 monthly 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

**Note:** #calves/#cows adjusts for cows without calves and averages energy for lactation across all individuals.

Holos V4 uses the following constant values:

*milk\_production* 8 (kg head-1 day-1)

*fat\_content* 4 (%)

**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 (ADG), 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 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)

***Note:*** *TDN* 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

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

##### Gross energy intake

**Eq. 3.1.1‑11**

IPCC 2019, Eq. 10.16

where

*GEI* Gross energy intake (MJ head-1 day-1)

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

##### 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)

**Note:** When a custom diet is created by the model user, *Ym* is first determined on the basis of the forage content – if forage content < 15%, a default *Ym* value of 0.04 is used. If forage content > 15% then the *Ym* is calculated based on the TDN content of the diet.

**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 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. 3.1.1‑14** 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 diet alternatives (≥ 25% dietary forage)

**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 alternatives (< 25% dietary forage)

**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)

*Starch* Starch intake (kg head-1 day-1)

Holos V4 uses the following calculations:

*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, we assume 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)] on the same pasture (native or tame) as the cows. Prior to that, the calves consume only milk only and thus generate no enteric CH4.

**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 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
* 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
* Three lactation periods each year are assumed, and milk production can be defined separately for each of these periods
* A single default management period for dairy calves of 3 months is assumed, during which time these animals are milk-fed only (after this, emissions for weaned calves may be calculated under a ‘Dairy heifers’ group). For all milk-fed-only dairy calves, enteric CH4 emissions are assumed to be zero
* 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)

***Note:*** *TDN* 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

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

##### Gross energy intake

**Eq. 3.2.1‑10**

IPCC (2019), Eq. 10.16

where

*GEI* Gross energy intake (MJ head-1 day-1)

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

##### 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

**For dairy calves:**

In Holos, a single default management period for pre-weaned dairy calves is assumed, during which time these animals are exclusively milk-fed and enteric CH4 emissions are assumed to be zero. **If the model user wishes to include a weaned dairy calf group, they should do this by adding another management period under the ‘Dairy heifers’ animal group to model emissions from older calves eating a partial or full forage diet**. To estimate the daily *Weight* of milk-fed dairy calves, Holos uses the same approach used for beef calves – see **Eq. 3.1.2‑1**. For dairy calves on a milk-only diet, the DMI is estimated as: ***DMI = Weight \* 0.01***. The GEI is also estimated using the beef calf approach – see **Eq. 3.1.2‑3**.

#### 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**).

##### High forage diets Alternatives (≥ 25% dietary forage)

**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**

##### Low forage diets Alternatives (< 25% dietary forage)

**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)

**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)

Holos V4 uses the following calculations:

*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. 3.2.1‑17**

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, **Eq. 3.2.2‑1** 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 days 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 and 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 uses the following constant value:

*EVmilk* 4.6 MJ kg-1 (IPCC 2019)

**For lactating ewes only (use only when ewes are lactating and milk production is known and 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 uses 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**

based on 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)

*Weight* Weight (kg head-1)

*ADG* Average daily gain (kg head-1 day-1), calculated using **Eq. 3.3.1‑9**

#### 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)

***Note:*** *TDN* 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

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

#### Gross energy intake

**Eq. 3.3.1‑13**

IPCC (2019), Eq. 10.16

where

*GE* Gross energy intake (MJ head-1 day-1)

***Note:*** *TDN* is to be entered as a percentage (e.g. as 81 not 0.81).

#### 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. 3.3.1‑15**

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 to yearly estimates

**Note:** **Scaling up of the detailed emission report to annual values has been disabled in V4**, and all outputs reported in Holos are currently for a single production cycle only. All 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 see below for the method to do so.

### 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).

This ‘scaling-up’ should be carried out in Holos for the following GHG emissions estimates reported in the Detailed Emission Report on the Results screen: ‘Enteric CH4’, ‘Manure CH4’, ‘Direct N2O’, ‘Indirect N2O’, ‘Farm energy CO2’, ‘Upstream CO2’ and ‘Subtotal’.

**Eq. 3.5.1‑1**

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. 3.5.1‑2**

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

## References

**3.1 Beef**

Ellis, J.L., Kebreab, E., Odongo, N.E., Beauchemin, K., McGinn, S., Nkrumah, J.D., Moore, S.S., Christopherson, R., Murdoch, G.K., McBride, B.W., Okine, E.K., France, J., 2009. Modeling methane production from beef cattle using linear and nonlinear approaches. J. Anim. Sci. 87, 1334–1345. https://doi.org/10.2527/jas.2007-0725.

Escobar-Bahamondes, P., Oba, M., Beauchemin, K., 2017. Universally applicable methane prediction equations for beef cattle fed high- or low-forage diets. Can. J. Anim. Sci. 94https://doi.org/10.1139/CJAS-2016-0042. CJAS-2016-0042.

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/>

Legesse G., Beauchemin K.A., Ominski K.H., McGeough E.J., Kroebel R., MacDonald D., Little S.M., and McAllister T.A., 2016. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Animal Production Science 56, 153-168. <https://doi.org/10.1071/AN15386>

Legesse, G., Cordeiro, M.R.C., Ominski, K.H., Beauchemin, K.A., Kroebel, R., McGeough, E.J., Pogue, S., and McAllister, T.A., 2018. Water use intensity of Canadian beef production in 1981 as compared to 2011. Sci. Total Environ. 619-620: 1030-1039. <https://doi.org/10.1016/j.scitotenv.2017.11.194>.

van Lingen, H.J., M. Niu, E. Kebreab, S. C. Valadares Filho, J. A. Rooke, C. Duthie, A. Schwarm, M. Kreuzer, P. I. Hynd, M. Caetano, M. Eugène, C. Martin, M. McGee, P. O’Kiely, M. Hünerberg, T. A. McAllister, T.T. Berchielli, J. D. Messana, N. Peiren, A. V. Chaves, Ed Charmley, N. A. Cole, K. E. Hales, S. Lee, A. Berndt, C. K. Reynolds, L. A. Crompton, A. Bayat, D. R. Yáñez-Ruiz, Z. Yu, A. Bannink, J. Dijkstra, D. P. Casper, A. N. Hristov. 2019. Prediction of enteric methane production, yield and intensity of beef cattle using an intercontinental database. Agriculture, Ecosystems and Environment 283 (2019) 106575. doi.org/10.1016/j.agee.2019.106575.

**3.2 Dairy**

Benaouda, M., Martin, C., Li, X., Kebreab, E., Hristov, A.N., Yu, Z., Yáñez-Ruiz, D.R., Reynolds, C.K., Crompton, L.A., Dijkstra, J., Bannink, A, Schwarm, A., Kreuzer, M., McGee, M., Lund, P., Hellwing, A.L.F., Weisbjerg, M.R., Moate, P. J., Bayat, A.R., Shingfield, K.J., Peiren, N., and Eugène, M., 2019. Evaluation of the performance of existing mathematical models predicting enteric methane emissions from ruminants: Animal categories and dietary mitigation strategies. Animal Feed Science and Technology 255, 114207. <https://doi.org/10.1016/j.anifeedsci.2019.114207>

Canadian Dairy Information Centre - Agriculture and Agri-Food Canada. Milk production by breed. [Online available: <http://www.dairyinfo.gc.ca/_english/dff/dff_2/dff_2b_e.htm> [accessed 1 November 2007].

Ellis, J.L., Kebreab, E., Odongo, N.E., McBride, B.W., Okine, E.K., France, J., 2007. Prediction of methane production from dairy and beef cattle. J. Dairy Sci. 90, 3456–3466. <https://doi.org/10.3168/jds.2006-675>

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/>

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E., France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. J. Anim. Sci. 81, 3141–3150. <https://doi.org/10.2527/2003.81123141x>.

Niu, M., Kebreab, E., Hristov, A.N., Oh, J., Arndt, C., Bannink, A., Bayat, A.R., Brito, A.F., Boland, T., Casper, D., Crompton, L.A., Dijkstra, J., Eugène, M.A., Garnsworthy, P.C., Haque, M.N., Hellwing, A.L.F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., Madsen, J., Martin, C., McClelland, S.C., McGee, M., Moata, P.J., Muetzel, S., Muñoz, C., O’Kiely, P., Peiren, N., Reynolds, C.K., Schwarm, A., Shingfield, K.J., Storlien, T.M., Weisbjerg, M.R., Yañez-Ruiz, D.R., Yu, A., 2018. Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. Glob Change Biol. 24: 3368– 3389. <https://doi.org/10.1111/gcb.14094>

Ramin, M, and Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. J Dairy Sci. 96(4):2476-2493. <https://doi.org/10.3168/jds.2012-6095>

**3.3 Sheep**

AFRC, 1990. *Nutritive Requirements of Ruminant Animals: Energy. Rep. 5*. Wallingford, UK: CAB International.

AFRC, 1993. *Energy and Protein Requirements of Ruminants* An advisory manual prepared by the AFRC (Agricultural and Food Research Council) Technical Committee on Response to Nutrients. Wallingford, UK: CAB International, pp. 24-159.

AFRC, 1995. *Energy and protein requirements of ruminants*. An advisory manual prepared by the AFRC (Agricultural and Food Research Council) Technical Committee on Response to Nutrients. Wallingford, UK: CAB International. pp 159.

Farm and Food Care Ontario, 2016. Facts and Figures about Canadian sheep. <https://www.farmfoodcareon.org/wp-content/uploads/2017/05/Fact-Sheet-Sheep-2016.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/>

**3.4 Swine, Poultry and others**

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/>

Vergé, X.P.X., Dyer, J.A., Desjardins, R.L., Worth, D. 2009. Greenhouse gas emissions from the Canadian pork industry. Livestock Science 121: 92-101. <https://doi.org/10.1016/j.livsci.2008.05.022>

**3.5 Scaling up of emissions estimates from production cycle to annual values**

New-Life Mills, 2016. Pullet and Layer Management Guide: A Complete Guide to Profitable Performance.Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22 (2), 205-223. <https://doi.org/10.1002/env.1044>

Sheppard, S.C., Bittman, S., Beaulieu, M., and Sheppard, M.I., 2009a. Ecoregion and farm-size differences in feed and manure nitrogen management: 1. Survey methods and results for poultry. Canadian Journal of Animal Science 89: 1-19. https://doi.org/10.4141/CJAS08054.

**Table 16**

Alemu, A. 2022. Personal communication. <https://profils-profiles.science.gc.ca/en/profile/aklilu-alemu-phd>

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/>

Lactanet, 2020. The Evolution of Lactanet Atlantic Dairy Production – 2019 Stats and Tips. Lactanet, Sainte-Anne-de-Bellevue, QC, Canada. Available at: <https://lactanet.ca/wp-content/uploads/2021/01/2019-atlantic_dairy_evolution_part_2.pdf>.

Sheppard, S.C., Bittman, S., Donohoe, G., Flaten, D., Wittenberg, K.M., Small, J.A., Berthiaume, R., McAllister, T.A., Beauchemin, K.A., McKinnon, J., Amiro, B.D., MacDonald, D., Mattos, F., Ominski, K.H., 2015. Beef cattle husbandry practices across Ecoregions of Canada in 2011. Canadian Journal of Animal Science 95: 305-321. <https://doi.org/10.4141/cjas-2014-158>.

**Table 17**

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 18**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

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/>

NASEM, 2016. Nutrient Requirements of Beef Cattle. Eighth Revised Edition. National Academies of Sciences, Engineering, and Medicine. Washington, DC: The National Academies Press. <https://doi.org/10.17226/19014>

**Table 19**

Darryl Gibb, Karen Beauchemin, Sean McGinn, AAFC - Pers. Comm.

**Table 20**

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 21**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

**Table 22**

Helgason, B.L., H.H. Janzen, D.A. Angers, M. Boehm, M. Bolinder, R.L. Desjardins, J. Dyer, B.H. Ellert, D.J. Gibb, E.G. Gregorich, R. Lemke, D. Massé, S.M. McGinn, T.A. McAllister, N. Newlands, E. Pattey, P. Rochette, W. Smith, A.J. VandenBygaart and H. Wang. 2005. GHGFarm: An assessment tool for estimating net greenhouse gas emissions from Canadian farms. Agriculture and Agri-Food Canada, Ottawa, ON, Canada.

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 23**

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 24**

Dimsoski, P., Tosh, J.J., Clay, J.C., and Irvin, K.M., 1999. Influence of management system on litter size, lamb growth, and carcass characteristics in sheep, Journal of Animal Science 77 (5), 1037–1043. <https://doi.org/10.2527/1999.7751037x>

**Tables 25 and 26**

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 27**

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/>

Vergé, X.P.X., Dyer, J.A., Desjardins, R.L., Worth, D. 2009. Greenhouse gas emissions from the Canadian pork industry. Livestock Science 121: 92-101. <https://doi.org/10.1016/j.livsci.2008.05.022>.

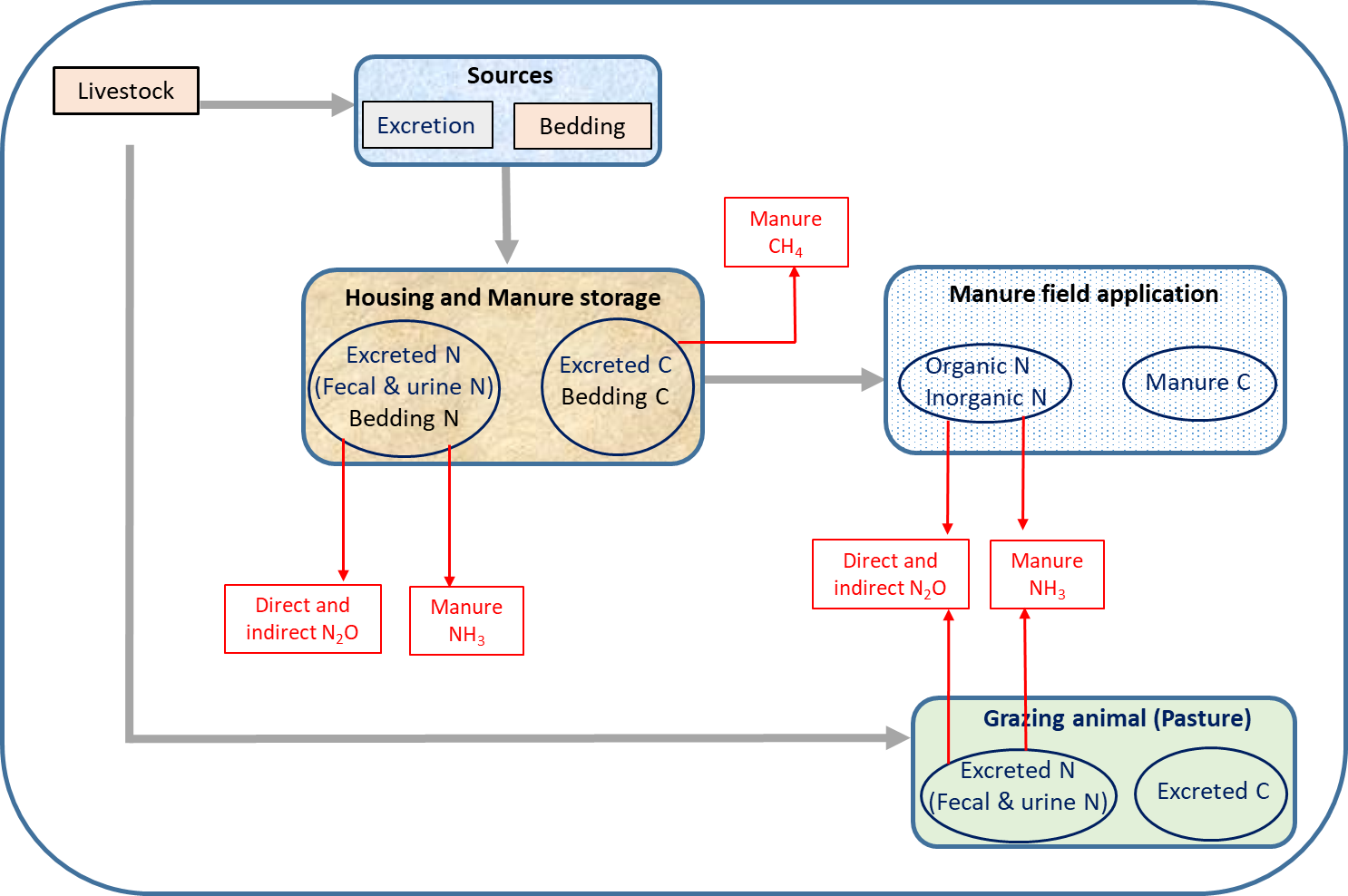
**Table 28**

Beaulieu, D., Pers. Comm.

New-Life Mills, 2016. Pullet and Layer Management Guide: A Complete Guide to Profitable Performance.Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22 (2), 205-223. <https://doi.org/10.1002/env.1044>

Sheppard, S.C., Bittman, S., Beaulieu, M., and Sheppard, M.I., 2009a. Ecoregion and farm-size differences in feed and manure nitrogen management: 1. Survey methods and results for poultry. Canadian Journal of Animal Science 89: 1-19. <https://doi.org/10.4141/CJAS08054>.

# Livestock manure: CH4 and N2O emissions from livestock housing and manure storage



**Figure 4.** 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 (from 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 V4. 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 currently not “scaled-up” to annual estimates by Holos. Instructions on how to do so manually is provided in section 3.5.**

**Beef cattle:** In Western Canada (except British Columbia, 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 may be 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 the decomposition of organic compounds). In a survey of beef cattle production systems in western Canada, roughly 30% 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 dairy farms use tie-stall barns and 31.7% use 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 New Brunswick (NB) to 77.8% in Newfoundland and Labrador (NFL)), while tie-stall barns dominated in Ontario (ON, 62.2%) and Québec (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 are generally 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 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 SK (10.6%), AB (18.3%), QC (22.2%) and ON (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 MB, 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 and deep pit under barn). 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, which are 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) (Chicken Farmers of Canada 2018; 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.

**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 ON. 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 ON (58.5%), Quebec (12.8%), and AB (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. 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 AB and BC in small scale operations, with an average of 8 to 10 animals per herd, but numbers in ON 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 AB and SK (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 AB and SK (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 C

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 animals grazing 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 uses 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 uses 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 “Pasture/range/paddock” should be used for sheep and other livestock (llamas and alpacas, deer and elk, goats, horses and mules, bison), while for all poultry the *Ccontent* value for solid poultry manure (with or without litter) is used (see **Table 6**)

**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 derived 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. 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 employ 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**).

**Note:** For livestock young (pre-weaned), we generally assume that bedding material applied for the adult females also accounts for the young, thus the default bedding application rates for pre-weaned animals are zero. However, if the user specifies a non-zero bedding application rate for these animal groups, the C (and N) from this bedding is considered in the Holos calculations.

**For all animal groups**

**Eq. 4.1.1‑6**

where

*Cbedding\_rate* Rate of C added from bedding material (kg head-1 day-1)

*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 manure. 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 animals grazing 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 manure (%), 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 calves on a partial or full forage diet, **Eq. 4.1.2‑1** is used.

***TDN* 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 kg-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 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 outdoor 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**

(adapted to daily calculation from Mangino et al. 2001)

where

*f* Climate factor

*T*1 308.16 K

*T*2 Average of the last 30-days air temperature (K)

*E* Activation energy constant (19,347 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 = 1 (IPCC, 2019), 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**

**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 daily into storage (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 (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 from storage before the end of the year/simulation period

If manure is removed from the storage system for application to land or export from the farm before the end of the year or simulation period, the amount of manure C and VS (for liquid manure only) remaining in the storage “tank” on the day following removal must be reduced by the relevant amount. For removals of manure for addition to an AD system, rather than adjusting the total stocks available in storage, the flows of manure (and the amounts of C, N, TAN, Organic N and VS contained therein) are adjusted as they ‘flow’ from storage into the pools available for land application, and therefore no further adjustment to the total available stocks is needed in this case – see text preceding **Eq. 4.8.1‑15**.   
**Note:** **the amounts of manure removed for land application or for export are currently not mutually exclusive.** Thus, if a total of 1,000 kg/L of manure are available in storage (following all housing and storage related VS, C and N losses and any prior transfers to the AD system), the user can apply 1,000 kg/L to land and can also export 1,000 kg/L from the farm. In a future version of Holos, it will no longer be possible to do this, and removals of manure for one purpose will automatically reduce the amount of manure available for other purposes.

**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), by livestock type and manure management system

*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. 4.1.3‑18**

where

*Total\_VSliquidstorage(t)* Amount of VS in stored liquid manure (kg VS) on day *t* (day following manure removal), by livestock type and manure management system

*Total\_VSliquidstorage(t-1)* Total amount of VS in stored liquid manure (kg VS) 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 or L) for application to land, calculated as: manure application rate (kg or L ha-1, specified by user) \* area of land receiving manure (ha, specified by user)

## **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 EF (*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 are used (**Table 36**).

### Total manure N

#### 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 (e.g., 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 uses 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 employs 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 *PI* and *PR* 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**

**Eq. 4.2.1‑13**

**Eq. 4.2.1‑14**

**Eq. 4.2.1‑15**

Derived from IPCC 2019, Eq. 10.31A

where

*PRsolid* Beef calf protein retained from solid feed (kg head-1 day-1)

*PRmilk* Beef calf protein retained from milk (kg head-1 day-1)

*PR* Beef calf protein retained (kg head-1 day-1)

*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) unless user-defined

*Skg* Live weight change of gilts or sows during gestation (kg head-1), calculated as: end weight – start weight

*350* Total number of days per year gilts or 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), if not user-defined

*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 of 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. For livestock young (pre-weaned), we generally assume that bedding material applied for the adult females also accounts for the bedding provided for the young, thus the default bedding application rates for pre-weaned animals are zero. However, if the user specifies a non-zero bedding application rate for these animal groups, the N (and C) from this bedding is considered in the Holos calculations.

**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)

*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**

**Eq. 4.2.1‑34**

where

*Nmanure* Amount of N in urine, faeces and bedding materials (kg N day-1), by animal group

*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* EF [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 emissions and NO3-N leaching/runoff during manure storage. In addition, some model parameters have been refined (e.g., updated EFs 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 (2019) default *Fracleach* and *EFleach* values. The sum of all volatilization and leaching/runoff N2O losses is equal to the total indirect N2O losses.

### 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 losses from animal housing and manure storage and grazing for each cattle group. This approach requires estimates of TAN excretion together with temperature-adjusted NH3 EFs (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 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 (based on 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).

**Note:** we assume that 100% of urinary N is excreted as urea.

**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 uses 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 as TAN (*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. 4.2.1‑32**

#### 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)

**Ammonia emissions from housing are calculated on a daily basis.**

**Eq. 4.3.1‑8**

where

*ATAfeedlot* Ambient temperature-based adjustments used to correct default NH3 EFs 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 (from NASA); 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 EF 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 ≤ *EFconfinednobarn\_adju* ≤ 1)

*EFconfinednobarn* Default NH3 EF 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

##### Beef cattle housed in barns (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.

**Ammonia emissions from housing are calculated on a daily basis.**

**Eq. 4.3.1‑12**

where

*ATAbarn* Ambient temperature-based adjustment used to correct default NH3 EFs for beef cattle barns

*T* Average daily outdoor temperature (°C) (from NASA)

**Eq. 4.3.1‑13**

where

*EFbarn\_adju* Adjusted NH3 EF for beef barns ((kg NH3-N kg-1 TAN ) (0 ≤ *EFbarn\_adju* ≤ 1)

*EFbarn* Default NH3 EF 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

### 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)

**Ammonia emissions from storage are calculated on a daily basis as an iterative loop.**

**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**

**For solid manure storage for dairy cattle (including calves):**

**Eq. 4.3.2‑4**

**For liquid manure storage for dairy cattle (including calves):**

**Eq. 4.3.2‑5**

where

*ATAsolidstorage\_beef* Ambient temperature-based adjustments used to correct default NH3 EFs for solid beef manure storage (deep bedding, solid storage/stockpiled, compost)

*ATAliquidstorage\_dairy* Ambient temperature-based adjustments used to correct default NH3 EFs for liquid dairy manure storage (tank, slurry pit, lagoon/earthen storage)

*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 outdoor air temperature

*T* Average daily outdoor temperature from NASA (°C)

**Eq. 4.3.2‑6**

where

*EFstorage\_adju* Adjusted NH3 EF (kg NH3-N kg-1 TAN ) for stored manure (0 ≤ *EFstorage\_adju* ≤ 1)

*EFstorage* Default NH3 EF 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**

#### 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), by livestock type and manure management system

*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 uses 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 (from 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* 0.25 (for housing on straw litter refreshed every 30 days or less, from 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

**Ammonia emissions from housing are calculated on a daily basis.**

**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 EFs 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

#### Manure NH3 volatilization from storage for broilers, layers and turkeys

**Ammonia emissions from storage are calculated on a daily basis.**

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 EFs 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 ≤ *EFstorage\_adju* ≤ 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

#### 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), by livestock type and manure management system

*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)

**Ammonia emissions from housing and storage are calculated on a daily basis.**

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)

#### 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

### N2O volatilization from manure in housing and storage for all livestock

**Indirect N2O emissions are calculated on a daily basis for all animal groups.**

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, default *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* EF 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

#### Adjustment of NH3 volatilization estimates from housing and storage following indirect N2O emissions

**Adjusted ammonia emissions from housing and storage are calculated on a daily basis.**

As indirect N2O emissions from livestock manure to the atmosphere are derived 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 reduced by the amount of indirect N2O emissions to avoid double-counting. 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* EF 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* EF 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

**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

**Eq. 4.3.6‑2**

**Eq. 4.3.6‑3**

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* EF for leaching [kg N2O-N (kg N)-1] (**Table 36**, by manure handling system)

*N2O-Nleaching* Manure leaching N emissions (kg N2O-N day-1), by animal group

*#animals* Number of animals

*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 S.J. Pogue, A.W. Alemu and P. Mantle)

### Total C 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 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**), including daily removals of manure for addition to an AD system (see **section 4.8.1.3**). 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.

**Note:** **the amounts of manure removed for land application or for export are currently not mutually exclusive.** Thus, despite only a total of 1,000 kg/L of manure being available in storage, the user can apply 1,000 kg/L to land and can also export 1,000 kg/L from the farm. In a future version of Holos, it will no longer be possible to do this, and removals of manure for one purpose will automatically reduce the amount of manure available for other purposes.

### Total N available in stored manure 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 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).   
**Note:** these amounts already reflect any previous removals of manure from storage for addition to an AD system (see **section 4.8.1.3**).

##### Total ammonical nitrogen (TAN)

**Eq. 4.5.2‑1**

**Eq. 4.5.2‑2**

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**

*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 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.   
**Note:** these amounts already reflect any previous removals of manure from storage for addition to an AD system (see **section 4.8.1.3**).

**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. 4.2.1‑32**

*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**

**Eq. 4.5.2‑7**

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

*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 removal (*t-1*), calculated as: manure application rate (kg ha-1, specified by user) \* area of land receiving manure (ha, specified by user), by livestock type and manure management system

*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**

**Eq. 4.5.2‑12**

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

*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**

**Eq. 4.5.2‑14**

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**

*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. 4.2.1‑32**

*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), by livestock type and manure management system

*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**

**Eq. 4.5.2‑22**

**Eq. 4.5.2‑23**

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. 4.2.1‑32**

*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**

*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

*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 land application 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 storage,by 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 and Eq. 6.3.2‑2) 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 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. 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 applied to a specific field:**

**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*.

**Note:** if digestate is also applied to field *n*, the digestate N applied is included in the *Total\_Nmanuretype(t,field n)* amount

*EFi,ON,l,m,n* EF 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, meaning that the EF is averaged across all available fields (excl. native rangeland, if present), weighted by their area.

**Eq. 4.6.1‑3**

where

EF 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 are 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 are: 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 EFs 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) (0 ≤ *ATAlandapplication* ≤ 1)[[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) (0 ≤ *EFlandapplication\_adju* ≤ 1)

*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 (excl. native rangeland, if present), meaning that the EF is averaged across these 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

EF 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**

where

*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

**Ammonia emissions from the land application of manure are calculated on a daily basis.**

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**.

Holos V4 uses 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**

where

*Total\_Nmanure\_export(t)* Total N exported from the farm in manure (kg N) in year *t*

**Eq. 4.6.2‑19**

where

*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 *Ncontent*/100 (%, 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 *Nlandmanure\_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*

### N2O volatilization from manure following land application

**Indirect N2O emissions from the land application of livestock manure are calculated on a daily basis.**

#### N2O emissions via volatilization during land application of farm-produced and imported manure and from exported manure

**To calculate indirect N2O emissions due to 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* EF 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*

**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*

**Eq. 4.6.3‑4**

Derived from IPCC (2019), Eq. 11.9

where

*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*

#### 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*

#### 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 the 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 the 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

**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).

**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*

*FracNleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* EF for leaching [kg N2O-N (kg N)-1], see box below

Holos V4 uses the following constant value:

*EFleach* 0.011 (IPCC 2019)

**Eq. 4.6.4‑2**

**Eq. 4.6.4‑3**

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*

*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*

*FracNleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* EF for leaching [kg N2O-N (kg N)-1], see box below

**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**

where

*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 and the ICBM soil C models 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 after 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* in year *t*:**

**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 (incl. leftover 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**

**Eq. 4.7.3‑2**

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**)

*Watermanure(t,field n)* Total amount of water in land-applied manure (mm), specific to field *n* in year *t*

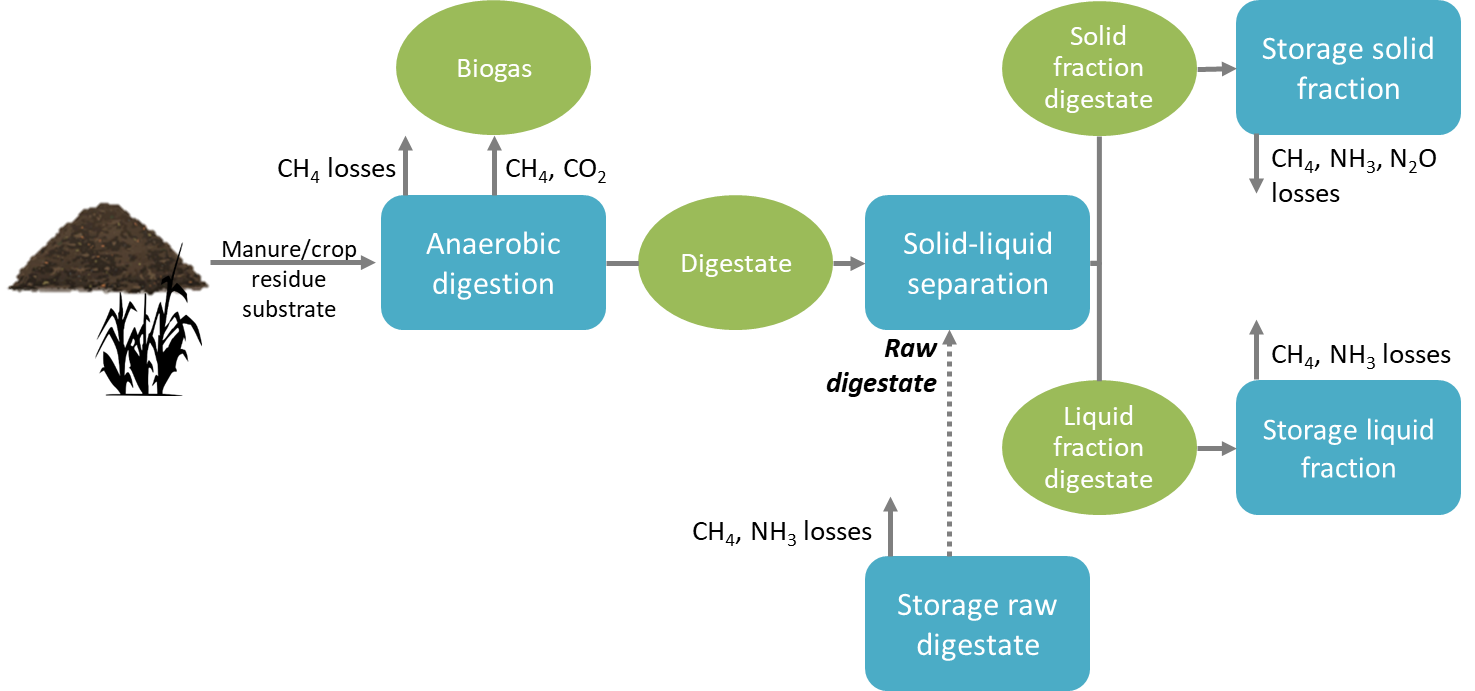
## Anaerobic digestion of livestock manure and crop residues

(by C. Vaneeckhaute 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
* Default digestate treatment: solid-liquid separation

The overall structure of the AD component is presented in **Figure 5**.



**Figure 5.** 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 these.

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.   
**Note:** **the addition of fresh/raw manure is not currently enabled in Holos V4**, but will be activated in a future update of the model.

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 based on 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 storage in different solid manure storage systems (**Table 45**). The kinetic rate of degradation of manure (*khydr,i*) also significantly reduces with age. The concentration of manure C and N 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 flowing into the total available manure pool each day that is transferred 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 derived from the literature.

### Flow of substrate, VS, N and C into the digester

#### For fresh/raw livestock manure entering the digester

This section outlines the approach used to estimate the flow of manure and manure nutrients when the user adds ‘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. Daily losses of C and N that occur during the housing stage are subtracted from this substrate before it enters the digester.

**Note:** the addition of fresh/raw manure is not currently enabled in Holos V4, but will be activated in a future update of the model.

***Flow of total mass of substrate entering the digester***

**Eq. 4.8.1‑1**

**Eq. 4.8.1‑2**

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

*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, the *Ncontent* values for ‘Manure (urine + feces) deposited on pasture’ are used

*Beddingappl\_rate*Bedding application rate (kg head-1 day-1), by animal group (userdefined or calculated using the Bedding Application Calculator)

*#animals* Number of animals, by animal group

*ManureADproportion,fm,i* Proportion of total daily manure produced added from the housing 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***

**Eq. 4.8.1‑3**

where

*TSflow,substrate,fm* Flow rate of total solids in substrate entering the digester from fresh manure (kg day-1)

*MoistureContentsubstrate,fm,i* Moisture content of substrate *i* (%) (**Table 6**), by livestock type and manure management system. **Note:** for fresh manure, the value for ‘Pasture/range/paddock’ is used

***Flow of VS entering the digester***

**Eq. 4.8.1‑4**

where

*VSflow,substrate,fm* Flow rate of VS entering the digester in fresh manure (kg day-1)

*VSfm,i* Volatile solids excreted (kg head-1 day-1), by animal group and manure management system, calculated using **Eq. 4.1.2‑1** for beef and dairy cattle and sheep and **Eq. 4.1.2‑3** for swine

*#animals* Number of animals, by animal group

***Flow of total N entering the digester***

**Eq. 4.8.1‑5**

where

*Nflow,substrate,fm* Flow rate of total N in fresh manure (incl. bedding) entering the digester (kg N day-1)

*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), **Eq. 4.3.1‑15** (barn housing for beef cattle) and **Eq. 4.3.3‑6** (poultry)

**Note:** As Holos V4 does not calculate estimates of NH3-N emissions from housing and storage separately for sheep, swine or other livestock, it is not currently possible to add ‘fresh’ manure from these livestock types to an AD system

***Flow of organic N entering the digester***

**For beef and dairy cattle:**

**Eq. 4.8.1‑6**

**For broilers, layers and turkeys:**

**Eq. 4.8.1‑7**

where

*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

*OrganicNflow,substrate,fm* Flow rate of organic N (kg N day-1 ) in fresh manure (incl. bedding) entering the digester

*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**

*TANexcretion,fm,i* Total ammonical N (TAN) excretion rate (kg TAN head-1 day-1).For broilers, layers and turkeys, default *TANexcretion\_rate* values are used (see Box associated with **Eq. 4.3.3‑5**)

***Flow of TAN entering the digester***

**Eq. 4.8.1‑8**

where

*TANflow,substrate,fm* Flow rate of TAN in fresh manure (incl. bedding) entering the digester (kg N day-1)

*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 and **Eq. 4.3.3‑7** for poultry

***Flow of total C entering the digester***

**Eq. 4.8.1‑9**

where

*Cflow,substrate,fm* Flow rate of total C in fresh manure (incl. bedding) entering the digester (kg day-1)

*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 wet weight 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 wet weight day-1) – user defined

***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 DM day-1)

*TSsubstrate,cr,I* Total solids concentration of crop residue, municipal sewage sludge, food waste or used vegetable oil *i* (kg DM t-1) (**Table 9** (for crop residues) and **Table 46** (for farm residues))

***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 9** (for crop residues) and **Table 46** (for farm residues))

***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 7** (for crop residues) and **Table 46** (for farm residues))

***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 DM is used for all crop residues; default values of 0.414 kg kg-1 DM (average of values from Odirile et al. (2021) for primary clarifier and microsieve treatments and from Serbanescu et al. (2017))[[12]](#footnote-13) and 0.475 kg kg-1 (DM basis, Esteves and Devlin (2010) – cited in Slorach et al. (2019)); are used for municipal sewage sludge and food waste, respectively. Due to a lack of data, no *Csubstrate* value is currently available for vegetable oil.

#### For livestock manure stored for a period of time prior to entering the digester

The model user has the option to add manure from a storage system to the anaerobic digester – this includes both solid and liquid manure types. This type of manure or AD substrate refers to manure removed from a manure storage system after all C and N losses during the housing and storage stages have been accounted for. Currently, in Holos V4, the option to add stored manure to an AD system is possible only for the major livestock groups, i.e., beef cattle, dairy cattle, sheep, swine and the major poultry groups (broilers, layers, pullets, turkeys), as the model does not currently estimate all required parameters for the AD calculations for other livestock types. The addition of stored manure from other livestock groups may be incorporated into a future version of Holos.

**Note:** the removal of manure and the C and N it contains from storage for addition to an AD system results in a reduction in the amount of manure, C and N that is then available for application to land or for export. The parameters that are adjusted in Holos to account for the daily transfer of manure from storage to an AD system are *Cflowstorage* (**Eq. 4.1.3‑14** for all livestock types), *TANflowstorage\_adju* (**Eq. 4.3.2‑8**/**Eq. 4.3.3‑11** for cattle and poultry), *OrganicNflowlandmanure* (**Eq. 4.5.2‑3** for cattle), *Nflowlandmanure* (**Eq. 4.5.2‑15** for poultry and **Eq. 4.5.2‑21** for sheep and swine), *VSavailable* (**Eq. 4.1.3‑5** for liquid dairy and swine manure). Following the aforementioned adjustments, *Volumelandmanure* (**Eq. 4.5.3‑2** for all livestock types) should adjust automatically.

***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 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 from a liquid or solid manure storage system (kg or L day-1), by animal group and manure management system

**For beef and dairy cattle and poultry:**

**Eq. 4.8.1‑16**

where

*TANflowstorage\_adju,sm,i* Flow of TAN into storage each day that is available for addition to an AD system (kg TAN), calculated using **Eq. 4.3.2‑8** for beef and dairy cattle and **Eq. 4.3.3‑11** for poultry. **Note:** this amount is exclusive of any prior TAN removals in ‘fresh’ manure from housing for addition to an AD system

*OrganicNflowlandmanure,sm,I* Flow of organic N into storage each day that is available for addition to an AD system (kg N), calculated using **Eq. 4.5.2‑3** for beef and dairy cattle. **Note:** this amount is exclusive of any prior organic N removals in ‘fresh’ manure from housing for addition to an AD system. For poultry, *OrganicNflowlandmanure* is calculated as: *Nflowlandmanure – TANflowstorage\_adju*, estimated using **Eq. 4.5.2‑15** and **Eq. 4.3.3‑11**, respectively

*Ncontent,sm,i* N content of stored manure (% wet weight), by animal group and manure management system (**Table 6**)

*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

**For sheep, swine and other livestock:**

**Eq. 4.8.1‑17**

where

*Nflowlandmanure,sm,I* Flow of N into storage each day that is available for addition to an AD system (kg N), calculated using **Eq. 4.5.2‑21**. **Note:** this amount is exclusive of any prior organic N removals in ‘fresh’ manure from housing for addition to an AD system

***Flow of TS entering the digester***

**Eq. 4.8.1‑18**

where

*TSflow,substrate,sm* Flow rate of total solids in substrate entering the digester from stored liquid or solid manure (kg day-1)

*MoistureContentsubstrate,sm,i* Moisture content of substrate *i* (%) (**Table 6**), by livestock type and manure management system

***Flow of VS entering the digester from liquid manure storage systems (dairy cattle and swine)***

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. For liquid manure, this is accounted for by considering the VS consumed during the pre-digester storage period.

**Eq. 4.8.1‑19**

where

*VSflow,substrate,slm* Flow rate of VS in stored liquid manure entering the digester (kg day-1)

*VSavailable,slm,i(t)* VS (kg) available in storage on day *t*, calculated using **Eq. 4.1.3‑5**, by animal group and manure management system

*Volumelandmanure,i* 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), calculated using **Eq. 4.5.3‑2**

***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. 4.8.1‑20**

where

*VSflow,substrate,ssm* Flow rate of VS in stored solid manure entering the digester from previously stored solid manure (kg day-1)

*Vssm,i* VS excreted (kg head-1 day-1), calculated using **Eq. 4.1.2‑1** for beef and dairy cattle and sheep, **Eq. 4.1.2‑3** for swine, and derived from **Table 34** for all other livestock types including poultry

*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. For all livestock groups, the following *VSreductionfactor* is applied: deep bedding: 0.65; all other solid manure types: 0.9

*#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. This is then adjusted by the proportion of the daily flow of manure that is added to the digester.

**For beef and dairy cattle:**

**Eq. 4.8.1‑21**

where

*Nflow,substrate,sm* Flow rate of total N in stored manure (liquid or solid) entering the digester (kg day-1)

**For broilers, layers, pullets and turkeys:**

*Nflow,substrate,sm,i* is calculated as *Nflowlandmanure,sm,i \* ManureADproportion,sm,i*, where *Nflowlandmanure* is estimated using **Eq. 4.5.2‑15**

**For all other livestock types:**

*Nflow,substrate,sm,i* is calculated as *Nflowlandmanure,sm,i \* ManureADproportion,sm,i*, where *Nflowlandmanure* is estimated using **Eq. 4.5.2‑21**.

***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 based on the flow of Organic N into the available pool, which is equal to the amount of organic N excreted minus all relevant housing and storage N losses. This is then adjusted by the proportion of the daily flow of manure that is added to the digester.

**Eq. 4.8.1‑22**

where

*OrganicNflow,substrate,sm* Flow rate of organic N in stored beef or dairy cattle manure (liquid or solid) entering the digester (kg day-1)

**For poultry:**

For the main poultry groups (broilers, layers, pullets and turkeys), the amount of Organic N 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, after all relevant housing and storage N losses have been considered.

**Eq. 4.8.1‑23**

where

*OrganicNflow,substrate,sm* Flow rate of organic N in stored solid poultry manure entering the digester (kg day-1)

*Nflow,substrate,sm* Flow rate of total N in stored solid poultry manure entering the digester (kg day-1)

*TANflow,substrate,sm* Flow rate of organic N in stored solid poultry manure entering the digester (kg day-1), calculated using **Eq. 4.8.1‑25**

***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, calculated using **Eq. 4.3.2‑8**. This is then adjusted by the proportion of stored manure added to the digester:

**Eq. 4.8.1‑24**

where

*TANflow,substrate,sm* Flow rate of TAN in stored beef or dairy cattle manure (liquid or solid) entering the digester (kg day-1)

*TANflowstorage\_adju,sm,i* Flow of TAN 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. 4.3.2‑8**

**For poultry:**

For broilers, layers, pullets 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 NH3-N losses.

**Eq. 4.8.1‑25**

where

*TANflow,substrate,sm* Flow rate of TAN in stored solid poultry manure entering the digester (kg day-1)

*TANflowstorage\_adju,sm,i* Flow rate of TAN in stored solid poultry manure entering the available pool for addition to the digestor (kg TAN), by animal group and manure management system, calculated using **Eq. 4.3.3‑11**

***Flow of total C entering the digester***

**Eq. 4.8.1‑26**

where

*Cflow,substrate,sm* Flow rate of total C in stored manure (liquid or solid) entering the digester (kg day-1)

*Cflowstorage,sm,i* Amount of C entering the available manure C pool (kg C day-1) by animal group and manure management system, calculated using **Eq. 4.1.3‑14** for all livestock types

#### For imported livestock manure

Manure imports to the anaerobic digester are specified through the ‘Manure type’ (Beef cattle, Dairy cattle, etc.), the ‘Manure handling system’ (Deep bedding, Liquid/Slurry with natural crust, etc.) and the amount of manure added to the digester on a daily basis (kg or L day-1). The model user can add imported manure for any of the livestock types and manure management systems available in Holos.

***Flow of total mass of substrate entering the digester in imported manure***

**Eq. 4.8.1‑27**

where

*Fflow,substrate,importedmanure* Flow rate of imported manure entering the digester (kg or L day-1)

*Fflow,substrate,importedmanure,i* Flow rate of imported manure type *i* entering the digester (kg or L day-1)

***Flow of TS entering the digester in imported manure***

**Eq. 4.8.1‑28**

where

*TSflow,substrate,importedmanure* Flow rate of total solids in substrate entering the digester from imported manure (kg day-1)

*MoistureContentsubstrate,importedmanure,i* Moisture content of substrate *i* (%) (**Table 6**), by livestock type and manure management system

***Flow of VS entering the digester in imported manure***

**Eq. 4.8.1‑29**

where

*VSflow,substrate,importedmanure* Flow rate of VS in imported manure entering the digester (kg VS day-1)

*VSsubstrate,importedmanure,i* VS concentration of substrate *i* (kg VS kg-1 wet weight) (**Table 6**), by livestock type and manure management system

***Flow of total N entering the digester in imported manure***

**Eq. 4.8.1‑30**

where

*Nflow,substrate,importedmanure* Flow rate of N in imported manure entering the digester (kg N day-1)

*Ncontent,importedmanure,i* N content of imported manure (% wet weight) (**Table 6**), by livestock type and manure management system

***Flow of total C entering the digester in imported manure***

**Eq. 4.8.1‑31**

where

*Cflow,substrate,importedmanure* Flow rate of C in imported manure entering the digester (kg C day-1)

*Ccontent,importedmanure,i* C content of imported manure (% wet weight) (**Table 6**), by livestock type and manure management system

### CH4 and biogas potential through anaerobic digestion

The CH4 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 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 CH4 potential

The CH4 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,i* Flow rate of biodegradable VS (kg day-1), by substrate type

*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 values for *fbiodeg,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), from **Eq. 4.8.2‑3**

*BMPi* Theoretical biomethane potential of substrate *i* (Nm3 t 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), by substrate type

*VSflow,biodeg,i* Flow rate of biodegradable VS in substrate *i* (kg day-1), by substrate type

*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 waste (Tait et al. 2008); 0.06 day-1 for manure dried in pads (for deep bedding) and 0.05 day-1 for stockpiled manure (for all other solid manure types) (Gopalan et al. 2013). **Note:** the *khydr* value for fresh manure is also used for stored liquid manure

*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), by substrate type

*CH4prod,i* Methane production of substrate *i* (Nm3 day-1)

*fCH4,i* Fraction of CH4 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)

#### CO2 production

#### Any biogas that is not converted into CH4 is transformed into CO2. The production of NH3, H2S and other trace compounds is 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 of 3.5 kg VS m-3 d-1 and average of 1.6 kg VS m-3 d-1 (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), thus 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 (kg 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 or 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. 4.8.1‑19** and **Eq. 4.8.1‑20** for fresh manure, crop residues, stored liquid manure and stored solid manure, respectively

#### 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 CH4 losses may arise.

**Eq. 4.8.2‑15**

where

*CH4grid* Potential CH4 injection to the gas grid (Nm3 day-1)

*fCH4,loss,upgrading* Fraction of methane lost in upgrading plants. A default value of 0.0081 is used (Kvist and Aryal, 2019)

**Note:** the *CH4grid* estimate can be subtracted from the total farm GHG emissions to use this CH4 to grid quantity as an offset, but only when the gas grid contains natural (fossil) gas that is being replaced by the *CH4grid* produced in the AD system.

### 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)

*VSflow,degraded* 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***

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***

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 solid-liquid 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. As a default, Holos uses solid-liquid separation coefficients for centrifuge separators (see **Table 47**), as this is generally the most efficient solid-liquid separation technique (Aguirre-Villegas et al. 2019; Guilayn et al. 2019), although a belt press solid-liquid separation option is also available as alternative.

***Total mass flow rate of raw material in liquid fraction and solid fraction***

**Eq. 4.8.4‑1**

**Eq. 4.8.4‑2**

where

*Fflow,digestate,LF* Flow rate of liquid fraction of digestate (kg/L 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/L day-1)

*Fdigestate,SF* Flow rate of solid fraction of digestate (kg/L day-1)

***Mass flow rate of TS in liquid fraction and solid fraction***

**Eq. 4.8.4‑3**

**Eq. 4.8.4‑4**

where

*TSflow,digestate,LF* Flow rate of TS in the liquid fraction of digestate (kg/L day-1)

*αTS*Separation coefficient: fraction of TS in the solid fraction following solid-liquid separation (**Table 47**)

*TSflow,digestate,SF* Flow rate of TS in the solid fraction of digestate (kg/L day-1)

***Mass flow rate of VS in liquid fraction and solid fraction***

**Eq. 4.8.4‑5**

**Eq. 4.8.4‑6**

where

*VSflow,digestate,LF* Flow rate of VS in the liquid fraction of digestate (kg/L day-1)

*αVS*Separation coefficient: fraction of VS in the solid fraction following solid-liquid separation (**Table 47**)

*VSflow,digestate,SF* Flow rate of VS in the solid fraction of digestate (kg/L 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/L day-1)

*TANflow,digestate,LF* Flow rate of TAN in the liquid fraction of digestate (kg/L day-1), calculated using **Eq. 4.8.4‑9**

*OrganicNflow,digestate,LF* Flow rate of organic N in the liquid fraction of digestate (kg/L 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/L day-1)

*TANflow,digestate,SF* Flow rate of TAN in the solid fraction of digestate (kg/L day-1), calculated using **Eq. 4.8.4‑10**

*OrganicNflow,digestate,SF* Flow rate of organic N in the solid fraction of digestate (kg/L 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 poultry)***

**Eq. 4.8.4‑9**

where

*TANflow,digestate,LF* Flow rate of TAN in the liquid fraction of digestate (kg/L 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/L day-1)

**Eq. 4.8.4‑10**

where

*TANflow,digestate,SF* Flow rate of TAN in the solid fraction of digestate (kg/L day-1)

***Mass flow rate of organic N in liquid fraction and solid fraction (for beef and dairy cattle and poultry)***

**Eq. 4.8.4‑11**

where

*OrganicNflow,digestate,LF* Flow rate of organic N in the liquid fraction of digestate (kg/L 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/L day-1)

**Eq. 4.8.4‑12**

where

*OrganicNflow,digestate,SF* Flow rate of organic N in the solid fraction of digestate (kg/L 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/L 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/L day-1)

**Eq. 4.8.4‑14**

where

*Cflow,digestate,SF* Flow rate of total C in the solid fraction of digestate (kg/L 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 EFs 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.

***CH4 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 EF 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 (kg/L), calculated using **Eq. 4.8.3‑1**

*1000000* Conversion from g CH4 m-3 digestate day-1 to kg CH4 kg-1 digestate day-1

Holos V4 uses the following equation to determine *ΥCH4,digestate* and the followingvalues for *ΥN2O,digestate* and*ΥNH3,digestate*:

*ΥCH4,digestate*Υ = 0.0176\*(Mean daily temperature (°C))2 – 0.0118\*Mean daily temperature (°C) + 0.0743

This equation is based on a temperature-ΥCH4 relationship derived from best-case scenario values from Maldaner et al. (2018), where Υspring = 1.72 g m-3 day-1 (11.6 °C); Υsummer = 5.75 g m-3 day-1 (18.6 °C); Υfall = 3.09 gm-3 day-1 (12.8 °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)

***N2O emissions during storage of digestate (whole, liquid and solid fractions)***

**Eq. 4.8.5‑2**

where

*N2Ostore,digestate* N2O emissions during digestate storage (kg day-1)

*ΥN2O,digestate* N2O EF for digestate storage (g m-3 day-1); see box above for default value

*1000000* Conversion from g N2O m-3 digestate day-1 to kg N2O kg-1 digestate day-1

***NH3 emissions during storage of digestate (whole, liquid and solid fractions)***

**Eq. 4.8.5‑3**

where

*NH3store,digestate* NH3 emissions during digestate storage (kg day-1)

*ΥNH3,digestate* NH3 EF for digestate storage (g m-3 day-1); see box above for default value

*1000000* Conversion from g NH3 m-3 digestate day-1 to kg NH3 kg-1 digestate day-1

**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 in storage. Therefore, the model estimates these values only for whole digestate. Once the required values/coefficients become available, a future version of Holos may allow the separate 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 (without entering a post-digester storage system), the amount of digestate, N and C, as well as ON and TAN available for application to land are equal to the flows of these from the digester.

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 solid-liquid 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 solid-liquid 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* - **Eq. 4.8.3‑1** (*Fflow,digestate*), *Total\_Volumelanddigestate,stored,LF* - **Eq. 4.8.4‑1** (*Fflow,digestate,LF*), and *Total\_Volumelanddigestate,stored,SF* - **Eq. 4.8.4‑2** (*Fflow,digestate,SF*).

For TAN and organic N (for beef and dairy cattle, broilers, layers and turkeys) and total N and total C (for all livestock types), 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,stored* 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* N2O emissions during digestate storage (kg N2O day-1), calculated using **Eq. 4.8.5‑2**

*NH3store,digestate* NH3 emissions during digestate storage (kg NH3 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,stored* 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* CH4 emissions during digestate storage (kg CH4 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 emissions and NO3 losses via leaching and runoff. The general approach used to estimate these N losses from land-applied digestate follows that used for land-applied manure, and land-applied digestate amounts are combined with land-applied manure amounts before estimating further N losses (see **section 4.6**).

### Direct N2O emissions from land-applied digestate

**Direct N2O emissions from the land application of digestate are calculated on a daily basis.**

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 (s**ection 4.6.1**), using the amounts of digestate N available for application to land: *Nlanddigestate,raw* (**Eq. 4.8.3‑4**), *Nlanddigestate,raw,LF* (**Eq. 4.8.4‑7**) or *Nlanddigestate,raw,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,stored, Nlanddigestate,stored,LF,* and*Nlanddigestate,stored,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* in year *t* (*N2O-Ndigestatedirect(t,field n)*) based on the specified digestate application rate for the field. Field-specific digestate N inputs to field *n* in year *t* (*Nlanddigestate(t,field n)*) are estimated based on the user-specified digestate application rate (kg ha-1) and the total amount of digestate and digestate N available for application 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 EF 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 (*N2O\_Nalldigestatedirect(t,field n)*) are estimated 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 from the land application of digestate are calculated on a daily basis.**

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, Eq. 4.6.2‑12**). 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 user-specified 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.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.

### Indirect N2O from Ammonia volatilization through digestate following land application

**Indirect N2O emissions after the land application of digestate are calculated on a daily basis.**

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.

#### Adjustment of NH3 volatilization estimates from land application of digestate following indirect N2O emissions

**Adjusted NH3 emissions from land application of digestate are calculated on a daily basis.**

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\_Ndigestatevolatilization\_adju* is equal to NH3-N emissions minus N2O-N emissions for both field-specific and leftover digestate applications (see **Eq. 4.6.3‑7** - **Eq. 4.6.3‑8**).

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.

### 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 (*FracNleach*) and the leaching EF (*EFleach*) – see **Eq. 4.6.4‑1** - **Eq. 4.6.4‑2**, where *FracNleach* 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), the leaching fraction (*FracNleach*) and *1-EFleach* – 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

*N2Odigestateindirect* 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 to estimate the amounts of C and N from land-spreaded digestate added to the soil C and N pools. The amount of C added serves as input to the IPCC Tier 2 and ICBM soil C models in Holos, while the amount of N added serves as input to the soil N2O emissions model (adapted from Liang et al. 2020). The amounts 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\_digestateremaining(t)* Remaining digestate C available for addition to the soil C pool after 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. 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 *Nlanddigestate(t,field n)* and *Nlanddigestateremaining(t,field n)*) minus all direct and indirect N losses from that field following land application of digestate (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 the general approach).

## References

**4. Livestock manure - Introduction**

Alpaca Livestock Producers and Cooperators Association, 2021. <https://www.alpaca.ca/>.

Bauman, C.A., Jones-Bitton, A., Menzies, P., Jansen, J., Kelton, D., 2016. Paratuberculosis on small ruminant dairy farms in Ontario, Canada: A survey of management practices. Can. Vet. J. 57: 523-530.

Canadian Agri-Food Research Council, 1996. Recommended code of practice for the fare and handling of farmed deer (Cervidae). Canadian Agri-Food Research Council, Ottawa, On, Canada. <https://www.nfacc.ca/pdfs/codes/deer_code_of_practice.pdf>.

Canadian Agri-Food Research Council, 2003. Recommended code of practice for the care and handling of farm animals: Goats. <https://www.nfacc.ca/pdfs/codes/goat_code_of_practice.pdf>.

Canadian Sheep Federation (2011) The Virtual Tool Box - Housing. <https://www.cansheep.ca/documents/VTB_Housing%20Section%202.pdf>.

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

Chicken Farmers of Canada, 2018. Chicken Farmers of Canada Animal Care Program Manual. <https://www.chickenfarmers.ca/wp-content/uploads/2014/07/ACP-Manual_2018_EN.pdf>

Dairy Farmers of Ontario 2007. Dairy cattle breeds. [Online] Available: <http://www.milk.org/Corporate/view.aspx?content=Students/DairyCattleBreeds> [accessed 1 November 2007].

Doris, P., n.d. Bedding Packs in Goat Barns. <https://ontariogoat.ca/wp-content/uploads/2011/10/bedding-packs-goats.pdf>

Farm and Food Care Ontario, 2016. Facts and Figures about Canadian Camelids. <https://www.farmfoodcareon.org/wp-content/uploads/2017/05/Fact-Sheet-Camelids-2016.pdf>.

Farm and Food Care Ontario, 2016. Facts and Figures about Canadian Deer and Elk. <https://www.farmfoodcareon.org/wp-content/uploads/2017/05/Fact-Sheet-Deer-Elk-2016.pdf>

Fowler, M.E., Bravo, P.W., 2010. Medicine and surgery of camelids (3rd ed.). Wiley-Blackwell: Ames, Iowa, USA. <https://doi.org/10.1002/9781118785706>.

Hofmann, N. and Beaulieu, M.S., 2006. A Geographical Profile of Manure Production in Canada, 2001. Statistics Canada Agriculture Division, Agriculture and Rural Working Paper Series. Published by authority of the Minister responsible for Statistics Canada, © Minister of Industry, 2006. Catalogue no. 21-601-MIE, ISSN 1707-0368, ISBN 0-662-42478-6, Ottawa, ON, Canada. <https://www150.statcan.gc.ca/n1/en/pub/21-601-m/21-601-m2006077-eng.pdf?st=9mxp6ymp>

MacMillan, K.M., Millican, L.J., Burns, J.J., Trenton McClure, J., Vanderstichel, R., 2020. Compliance with the Code of Practice for the Care and Handling of Equines on 50 horse farms in Prince Edward Island. Can. Vet. J. 61: 985-989.

Molnar, S., and Wright, B., 2006. Evaluating performance of several horse beddings. Info Sheet, Agricultural Information Contact Centre, Ontario Ministry of Agriculture, Food and Rural Affairs. ORDER NO. 06-105, AGDEX 460/20 <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.483.4097&rep=rep1&type=pdf>

NFACC, 2013a. Code of Practice for the Care and Handling of Sheep. National Farm Animal Care Council, Lacombe, AB, Canada. <https://www.nfacc.ca/codes-of-practice/sheep>

NFACC, 2013b. Code of Practice for the Care and Handling of Equines. National Farm Animal Care Council, Lacombe, AB, Canada. <https://www.nfacc.ca/codes-of-practice/equine>.

NFACC, 2017. Code of Practice for the Care and Handling of Bison. National Farm Animal Care Council, Lacombe, AB, Canada. <https://www.nfacc.ca/codes-of-practice/bison>.

Nova Scotia Department of Agriculture, n.d. Goat Production Manual. A Guide for 4-H Leaders and Beginning Farmers. <https://novascotia.ca/thinkfarm/documents/Manual-Goat.pdf>.

Panza, D. 2020. Effects of past grazing and trampling on soil nutrients at Stanley Hill Bison, Kakabeka Falls, Ontario. Unpublished undergraduate thesis, Lakehead University, Thunder Bay, ON, Canada. <http://knowledgecommons.lakeheadu.ca/handle/2453/4589>.

Province of Manitoba, 2021. Sheep manure management. <https://www.gov.mb.ca/agriculture/livestock/sheep/print,manure-management.html>.

Rioja-Lang, F.C., Galbraith, J.K., McCorkell, R.B., Spooner, J.M., Church, J.S., 2019. Review of priority welfare issues of commercially raised bison in North America. Applied Animal Behaviour Science, 210, 1-8. <https://doi.org/10.1016/j.applanim.2018.10.014>.

Sheppard S. C., Bittman S., Swift M., and Tait J., 2011a. Modelling monthly NH3 emissions from dairy in 12 Ecoregions of Canada. Canadian Journal of Animal Science 91: 649-661. <https://doi.org/10.4141/cjas2010-005>

Sheppard S. C., Bittman S., Swift M., Beaulieu M., and Sheppard M., 2011b. Ecoregion and farm size differences in dairy feed and manure-Nitrogen management: A survey. Canadian Journal of Animal Science 91: 459-473. <https://doi.org/10.4141/cjas2010-004>

Sheppard, S.C., and Bittman, S., 2012. Farm practices as they affect NH3 emissions from beef cattle. Can. J. Anim. Sci. 92: 525-543. <https://doi.org/10.4141/cjas2012-055>.

Statistics Canada, 2021. Statistics Canada. Table 32-10-0129-01 Number of sheep and lambs on farms (x 1,000). Statistics Canada, Ottawa, ON, Canada. <https://doi.org/10.25318/3210012901-eng>.

Statistics Canada, 2022. Table 32-10-0373-01 Other livestock inventories on farms. Census of Agriculture, 2021. Statistics Canada, Ottawa, On, Canada. <https://doi.org/10.25318/3210037301-eng>.

University of Guelph, 2015. National Dairy Study – At a Glance. <https://www.nationaldairystudy.ca/at-a-glance>

**4.1 Manure carbon**

Aguerre, M.J., Wattiaux, M.A., and Powell, J.M., 2012. Emissions of ammonia, nitrous oxide, methane, and carbon dioxide during storage of dairy cow manure as affected by dietary forage-to-concentrate ratio and crust formation. Journal of Dairy Science 95 (12), 7409-7416. <https://doi.org/10.3168/jds.2012-5340>

Amon, B., Kryvoruchko, V., Amon, T., and Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture, Ecosystems and Environment 112, 153–162. <https://doi.org/10.1016/j.agee.2005.08.030>

Amon, B., Kryvoruchko, V., Fröhlich, M., Amon, T., Pöllinger, A., Mösenbacher, I., and Hausleitner, A., 2007. Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: housing and manure storage. Livestock Science 112, 199–207. <https://doi.org/10.1016/j.livsci.2007.09.003>

Baron, V.S., Mapfume, E., Dick, A.C., Naeth, M.A., Okine, E.K., and Chanasyk, D.S., 2002. Grazing intensity impacts on pasture carbon and nitrogen flow. Journal of Range Management 55(6), 535-541. <https://doi.org/10.2307/4003996>

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

Clemens, J., Trimborn, M., Weiland, P., Amon, B., 2006. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agric. Ecosyst. Environ. 112, 171–177. <http://dx.doi.org/10.1016/j.agee.2005.08.016>

Guarino, M., Fabbri, C., Brambilla, M., Valli, L., and Navarro, P., 2006. Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. Trans. ASAE, 49 (2006), pp. 737-747. <https://doi.org/10.13031/2013.20481>

Hou, Y., Velthof, G.L., and Oenema, O., 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Glob Chang Biol 21: 1293-1312. <https://doi.org/10.1111/gcb.12767>

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/>

Jarret, G., Cozannet, P., Martinez, J., and Dourmad, J.Y., 2011. Effect of different quality wheat dried distiller’s grain solubles (DDGS) in pig diets on composition of excreta and methane production from faeces and slurry. Livest. Sci. 140:275–282. <https://doi.org/10.1016/j.livsci.2011.04.006>

Jørgensen, H., Prapaspongsa, T., Vu, V., and Poulsen, H, 2013. Models to quantify excretion of dry matter, nitrogen, phosphorus and carbon in growing pigs fed regional diets. Journal of animal science and biotechnology 4, 42. <https://doi.org/10.1186/2049-1891-4-42>

Larney, F. J., Olson, A. F., Miller, J. J., DeMaere, P. R., Zvomuya, F. and McAllister, T. A. 2008. Physical and chemical changes during composting of wood chip-bedded and straw-bedded beef cattle feedlot manure. J. Environ. Qual. 37: 725735. <https://doi.org/10.2134/jeq2007.0351>

Mangino J., Bartram D., and Brazy A., 2001. Development of a Methane Conversion Factor to Estimate Emissions from Animal Waste Lagoons. USEPA Technical Report, Washington, D. C.: Environmental Protection Agency. pp. 14. <https://www3.epa.gov/ttnchie1/conference/ei11/ammonia/mangino.pdf>

Matulaitis, R., Juskiené, V., and Juska, R., 2015. The effect of floating covers on gas emissions from liquid pig manure. Chilean Journal of Agricultural Research 75: 232-238. <http://dx.doi.org/10.4067/S0718-58392015000200013>

Misselbrook, T., Hunt, J., Perazzolo, F., and Provolo, G., 2016. Greenhouse gas and ammonia emissions from slurry storage: impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). Journal of Environmental Quality 45: 1520-1530. <https://doi.org/10.2134/jeq2015.12.0618>

Nielsen, D.A., Schramm, A., Nielsen, L.P., and Revsbech, N.P., 2013. Seasonal methane oxidation potential in manure crusts. Applied and environmental microbiology 79: 407-410. <https://doi.org/10.1128/AEM.02278-12>

Olson, E.C.S., D.S. Chanasyk, and J.J. Miller. 2006. Effects of bedding type and within-pen location on feedlot runoff. Trans. ASABE 49:905–914. <https://doi.org/10.13031/2013.21736>

Rotz, C.A., Isenberg, B., Stackhouse-Lawson, K., and Pollak, E., 2013. A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. Journal of animal science. 91, 5427-5437. <https://doi.org/10.2527/jas.2013-6506>

VanderZaag, A.C., Gordon, R.J., Glass, V.M., and Jamieson, R.C., 2008. Floating covers to reduce gas emissions from liquid manure storages: a review. Applied Engineering in Agriculture 24: 657. <https://doi.org/10.13031/2013.25273>

VanderZaag, A.C., Gordon, R.J., Jamieson, R.C., Burton, D.L., and Stratton, G.W., 2009. Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. Transactions of the Asabe 52: 599. <https://doi.org/10.13031/2013.26832>

Vergé, X., Worth, D., Hutchinson, J.J., and R.L. Desjardins. 2006. Greenhouse Gas Emissions from Agro-Ecosystems in Canada. Methane Emissions - Technical report: methodology for calculations. Agriculture and Agri-Food Canada (AAFC)/Agriculture et Agroalimentaire Canada (AAC). (Report) 38 pp

**4.2 Direct N2O**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

FAO, 2017. Global Livestock Environmental Assessment Model v2.0. Data reference year 2010. Revision 4, June 2017. Rome, Italy: Food and Agriculture Oganization of the United Nations. Available at: <http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf>

Greenhouse Gas System Pork Protocol: The Innovative Feeding of Swine and Storing and Spreading of Swine Manure (Draft) dated July 31, 2006. Prepared by the Pork Technical Working Group (PTWG), a sub-committee of the National Offsets Quantification Team (NOQT).

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/>

Janzen, H.H., Angers, D.A., Boehm, M., Bolinder, M., Desjardins, R.L., Dyer, J.A., Ellert, B.H., Gibb, D.J., Gregorich, E.G., Helgason, B.L., Lemke, R., Massé, D., McGinn, S.M., McAllister, T.A., Newlands, N., Pattey, E., Rochette, P., Smith, W., VandenBygaart, A.J., and Wang, H., 2006. A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. Canadian Journal of Soil Science 86: 401–418. <https://doi.org/10.4141/S05-101>

Legesse G., Beauchemin K.A., Ominski K.H., McGeough E.J., Kroebel R., MacDonald D., Little S.M., and McAllister T.A., 2016. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Animal Production Science 56, 153-168. <https://doi.org/10.1071/AN15386>

NASEM, 2016. Nutrient Requirements of Beef Cattle. Eighth Revised Edition. National Academies of Sciences, Engineering, and Medicine. Washington, DC: The National Academies Press. <https://doi.org/10.17226/19014>

National Research Council. 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition: Update 2001. National Academy Press, Washington, USA.

**4.3 Indirect N2O**

Bogan, B.W., Chandrasekar, A., McGlynn, S., Gooch, C.A., Heber, A.J., 2010. National Air Emissions Monitoring Study: Data from Dairy Freestall Barn and Milking Center in New York-Site NY5B. Final Report. Purdue University, West Lafayette, IN, July 2.

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

Dong, R.L., Zhao, G.Y., Chai, L.L., and Beauchemin, K.A., 2014. Prediction of urinary and fecal nitrogen excretion by beef cattle. J Anim Sci. 92(10):4669-81. <https://doi.org/10.2527/jas.2014-8000>

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

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/>

Ramirez-Dorronsoro, J.C., Joo, H.S., Ndegwa, P., Heber, A.J., July 30 2010. National Air Emissions Monitoring Study: Data from Two Dairy Freestall Barns in Washington WA5B. Final Report. Purdue University, West Lafayette, IN.

Sheppard, S.C., Bittman, S., Beaulieu, M., and Sheppard, M.I., 2009a. Ecoregion and farm-size differences in feed and manure nitrogen management: 1. Survey methods and results for poultry. Canadian Journal of Animal Science 89: 1-19. https://doi.org/10.4141/CJAS08054.

Sheppard, S.C., Bittman, S., and Tait, J., 2009b. Monthly NH3 emissions from poultry in 12 ecoregions of Canada. Canadian Journal of Animal Science 89: 21-35. <https://doi.org/10.4141/CJAS08055>.

Sheppard, S.C., and Bittman, S., 2012. Farm practices as they affect NH3 emissions from beef cattle. Can. J. Anim. Sci. 92: 525-543. <https://doi.org/10.4141/cjas2012-055>.

Sheppard S. C., Bittman S., Swift M., and Tait J., 2011a. Modelling monthly NH3 emissions from dairy in 12 Ecoregions of Canada. Canadian Journal of Animal Science 91: 649-661. <https://doi.org/10.4141/cjas2010-005>

Sheppard S. C., Bittman S., Swift M., Beaulieu M., and Sheppard M., 2011b. Ecoregion and farm size differences in dairy feed and manure-Nitrogen management: A survey. Canadian Journal of Animal Science 91: 459-473. <https://doi.org/10.4141/cjas2010-004>

Sims, J.T., and Stehouwer, R.C., 2008. Recycling of Nitrogen through Land Application of Agricultural, Municipal, and Industrial By-products. In Nitrogen in Agricultural Systems (eds J.S. Schepers and W.R. Raun). <https://doi.org/10.2134/agronmonogr49.c20>

**4.6 Emissions from land application - manure**

AAFC, 2016. Canadian Manure Management Practices on Cropland from the Farm Environmental Management Survey (FEMS) 2011. Agriculture and Agri-Food Canada, Ottawa, ON, Canada, pp 67

Bittman, S., Sheppard, S.C., and Hunt, D., 2017. Potential for mitigating atmospheric ammonia in Canada. Soil Use Manage, 33: 263-275. https://doi.org/10.1111/sum.12336

Brentrup, F., Küsters, J., Lammel, J., and Kuhlmann, H., 2000. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int. J. LCA 5, 349. <https://doi.org/10.1007/BF02978670>

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

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/>

Sheppard, S.C., Bittman, S., and Tait, J., 2009b. Monthly NH3 emissions from poultry in 12 ecoregions of Canada. Canadian Journal of Animal Science 89: 21-35. <https://doi.org/10.4141/CJAS08055>.

Sheppard S. C., Bittman S., Swift M., and Tait J., 2011a. Modelling monthly NH3 emissions from dairy in 12 Ecoregions of Canada. Canadian Journal of Animal Science 91: 649-661. <https://doi.org/10.4141/cjas2010-005>

**4.8 Anaerobic digestion**

Aguirre-Villegas, H.A., Larson, R.A., Sharara, M.A., 2019. Anaerobic digestion, solid-liquid separation, and drying of dairy manure: Measuring constituents and modeling emission. Science of the Total Environment 696: 134059. <https://doi.org/10.1016/j.scitotenv.2019.134059>

Bareha, Y., Affes, R., Moinard, Y., Buffet, J., and Girault, R., 2021. A simple mass balance tool to predict carbon and nitrogen fluxes in anaerobic digestion systems. Waste Management 135, 47-59. <https://doi.org/10.1016/j.wasman.2021.08.020>

Cornell, 1996. Estimating carbon content. Cornell Waste Management Institute, Cornell University, NY, USA. <http://compost.css.cornell.edu/calc/carbon.html>

EMU, 2021. Cogeneration / Combined heat and power (CHP). Course notes, Eastern Mennonite University, VA, USA. <https://staff.emu.edu.tr/devrimaydin/Documents/MENG446/Chapter%205%20Combined%20Heat%20and%20Power.pdf>

Esteves, S., and Devlin, D., 2010. Food Waste Chemical Analysis. [Online]. WRAP. Available: [www.wrapcymru.org.uk/sites/files/wrap/Technical\_report\_food\_waste characterisation\_Wales\_2009x2.9086.pdf](http://www.wrapcymru.org.uk/sites/files/wrap/Technical_report_food_waste%20characterisation_Wales_2009x2.9086.pdf)

Flesch, T.K., Desjardins, R.L., and Worth, D., 2011. Fugitive methane emissions from an agricultural biodigester. Biomass and Bioenergy 35(9), 3927-3935. <https://doi.org/10.1016/j.biombioe.2011.06.009>

Gopalan, P., Jansen, P., and Batstone, D., 2013. Biochemical methane potential of beef feedlot manure: Impact of manure age and storage. Journal of Environmental Quality 42: 1205-12. <https://doi.org/10.2134/jeq2012.0457>

Hamilton, D.W., 2017. Anaerobic digestion of animal manures: Types of digesters. Oklahoma State University, OK, USA. <https://extension.okstate.edu/fact-sheets/anaerobic-digestion-of-animal-manures-types-of-digesters.html>

Kvist, T., and Aryal, N., 2019. Methane loss from commercially operating biogas upgrading plants. Waste Management 87, 295-300. <https://doi.org/10.1016/j.wasman.2019.02.023>

Liebetrau, J., Torsten, R., Agostini, A., and Linke, B., 2017. Methane emissions from biogas plants. Methods for measurement, results and effect on greenhouse gas balance of electricity produced. IEA Bioenergy: Task 37. <https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf>

Maldaner, L., Wagner-Riddle, C., VanderZaag, A.C., Gordon, R., and Duke, C., 2018. Methane emissions from storage of digestate at a dairy manure biogas facility. Agricultural and Forest Meteorology 259, 96-107. <https://doi.org/10.1016/j.agrformet.2017.12.184>

Odirile, P.T., Marumoloa, P.M., Manali, A., and Gikas, P., 2021. Anaerobic digestion for biogas production from municipal sewage sludge: A comparative study between finr mesh sieved primary sludge and sedimented primary sludge. Water 13: 3532. <https://doi.org/10.3390/w13243532>

PSU, 2012. Anaerobic digestion: Biogas production and odor reduction. PennState Extension, Pennsylvania State University, PA, USA. <https://extension.psu.edu/anaerobic-digestion-biogas-production-and-odor-reduction>

Serbanescu, A., Barbu, M., Nicolescu, I., and Bucur, E., 2017. Interdependence between total organic carbon content and heating value of sewage sludge samples. International Symposium “The Environment and the Industry”, SIMI 2017, Proceedings Book. <http://doi.org/10.21698/simi.2017.0035>

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., and Azapagic, A., 2019. Environmental sustainability of anaerobic digestion of household food waste. Journal of Environmental Management 236: 798-814. <https://doi.org/10.1016/j.jenvman.2019.02.001>

Tait, S., Astals, S., Batstone, D., and Jensen, P., 2008. Enhanced methane bioenergy recovery at Australian piggeries through anaerobic co-digestion. Final report prepared for the Cooperative Research Centre for High Integrity Australian Pork. <http://porkcrc.com.au/wp-content/uploads/2018/02/4C-113-Project-Final-Research-Report.pdf>

Vergote, T.L.I., Bodé, S., De Dobbelaere, A.E.J., Buysse, J., Meers, E., and Volcke, E.I.P., 2020. Monitoring methane and nitrous oxide emissions from digestate storage following manure mono-digestion. Biosystems Engineering 196, 159-171. <https://doi.org/10.1016/j.biosystemseng.2020.05.011>

Walling, E., and Vaneeckhaute, C., 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. Journal of Environmental Management 276, 111211. <https://doi.org/10.1016/j.jenvman.2020.111211>

Wilkie, A.C., 2005. Anaerobic digestion of dairy manure: Design and process considerations. In: Dairy manure management: Treatment, handling, and community relations. NRAES-176, p. 301-312. Natural Resource, Agriculture, and Engineering Service, Cornell University, NY, USA. <https://biogas.ifas.ufl.edu/Publs/NRAES176-p301-312-Mar2005.pdf>

**4.9 Emissions from land application - digestate**

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 6**

See **section 2.8** for references

**Table 18**

See **section 3.6** for references

**Table 26**

See **section 3.6** for references

**Table 29**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

Hofmann, N. and Beaulieu, M.S., 2006. A Geographical Profile of Manure Production in Canada, 2001. Statistics Canada Agriculture Division, Agriculture and Rural Working Paper Series. Published by authority of the Minister responsible for Statistics Canada, © Minister of Industry, 2006. Catalogue no. 21-601-MIE, ISSN 1707-0368, ISBN 0-662-42478-6, Ottawa, ON, Canada. <https://www150.statcan.gc.ca/n1/en/pub/21-601-m/21-601-m2006077-eng.pdf?st=9mxp6ymp>

Lorimor, J., Powers, W., Sutton, A. 2004. Manure Characteristics: Manure Management Systems Series. MWPS-18 Section 1. Second Edition. Available at: <https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf>

**Table 30**

Canadian Sheep Federation / Fédération canadienne du mouton, 2021. Virtual Tool Box – Housing. Available at: <https://www.cansheep.ca/resources.html>.

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

Ferraz, P.F.P., Ferraz, G.A.S., Leso, L., Klopčič, M., Barbari, M., Rossi, G., 2020. Properties of conventional and alternative bedding materials for dairy cattle. Journal of Dairy Science, 103 (2020), <https://doi.org/10.3168/jds.2020-18318>

Gilhespy, S.L., Webb, J., Chadwick, D., Misselbrook, T., Kay, R., Camp, V., Retter, A.L., and Bason, A., 2009. Will additional straw bedding in buildings housing cattle and pigs reduce ammonia emissions?. Biosystems Engineering 102, 180-189. <https://doi.org/10.1016/j.biosystemseng.2008.10.005>

Lactanet, 2020. The Evolution of Lactanet Atlantic Dairy Production – 2019 Stats and Tips. Lactanet, Sainte-Anne-de-Bellevue, QC, Canada. Available at: <https://lactanet.ca/wp-content/uploads/2021/01/2019-atlantic_dairy_evolution_part_2.pdf>.

Larney, F. J., Olson, A. F., Miller, J. J., DeMaere, P. R., Zvomuya, F. and McAllister, T. A. 2008. Physical and chemical changes during composting of wood chip-bedded and straw-bedded beef cattle feedlot manure. J. Environ. Qual. 37: 725735. <https://doi.org/10.2134/jeq2007.0351>

Lorimor, J., Powers, W., Sutton, A. 2004. Manure Characteristics: Manure Management Systems Series. MWPS-18 Section 1. Second Edition. Available at: <https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf>

Misselbrook, T.H., Powell, J.M., Broderick, G.A., and Grabber, J.H., 2005. Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. J Dairy Sci. 88(5), 1765-77. <https://doi.org/10.3168/jds.S0022-0302(05)72851-4>

OMAFRA, 2015. Using separated manure solids for compost bedding. Factsheet 15-019. Agdex 410/721. <https://www.ontario.ca/page/using-separated-manure-solids-compost-bedding#:~:text=Composted%20bedding%20from%20drum%20composters&text=Solids%20from%20liquid%20manure%20are,kill%20most%20of%20the%20pathogens>.

Rotz, C.A., Isenberg, B., Stackhouse-Lawson, K., and Pollak, E., 2013. A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. Journal of animal science. 91, 5427-5437. <https://doi.org/10.2527/jas.2013-6506>

**Tables 31 & 32**

Greenhouse Gas System Pork Protocol: The Innovative Feeding of Swine and Storing and Spreading of Swine Manure (Draft) dated July 31, 2006. Prepared by the Pork Technical Working Group (PTWG), a sub-committee of the National Offsets Quantification Team (NOQT)

**Table 33**

Beaulieu, D. Pers. Comm.

**Table 34**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

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/>

Pelletier, N., 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. Journal of Cleaner Production 152, 167-180. <https://doi.org/10.1016/j.jclepro.2017.03.050>

**Table 35**

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 36**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

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 37**

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 38**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

FAO, 2002. FAO Animal Production and Health Paper – 154. Food and Agriculture Organization of the United Nations, Rome, Italy. <http://www.fao.org/3/Y4359E/y4359e00.htm#Contents>

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 39**

Beaulieu, D. Pers. Comm.

**Table 40**

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 41**

Farm and Food Care Ontario, 2016. Facts and Figures about Canadian Hens and Eggs. <https://www.farmfoodcareon.org/wp-content/uploads/2017/05/Hen-and-Egg-fact-sheet-2016final.pdf>

Let’s Talk Chicken (<https://letstalkchicken.ca/farm-to-table/chicken-farm/>)

New-Life Mills, 2016. Pullet and Layer Management Guide: A Complete Guide to Profitable Performance.Newlands, N.K., Davidson, A., Howard, A., and Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22 (2), 205-223. <https://doi.org/10.1002/env.1044>

Pelletier, N., 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. Journal of Cleaner Production 152, 167-180. <https://doi.org/10.1016/j.jclepro.2017.03.050>

Sheppard, S.C., Bittman, S., Beaulieu, M., and Sheppard, M.I., 2009a. Ecoregion and farm-size differences in feed and manure nitrogen management: 1. Survey methods and results for poultry. Canadian Journal of Animal Science 89: 1-19. https://doi.org/10.4141/CJAS08054.

**Table 42**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

FAO, 2002. FAO Animal Production and Health Paper – 154. Food and Agriculture Organization of the United Nations, Rome, Italy. <http://www.fao.org/3/Y4359E/y4359e00.htm#Contents>

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 43**

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

**Table 44**

Chai, L., Kröbel, R., Janzen, H.H., Beauchemin, K.A., McGinn, S.M., Bittman, S., Atia, A., Edeogu, I., MacDonald, D., and Dong, R., 2014. A regional mass balance model based on total ammoniacal nitrogen for estimating ammonia emissions from beef cattle in Alberta Canada. Atmos. Environ. 92: 292–302. <https://doi.org/10.1016/j.atmosenv.2014.04.037>

Chai, L., Kröbel, R., Macdonald, D., Bittman, S., Beauchemin, K., Janzen, H., McGinn, S., and Vanderzaag, A., 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. Atmospheric Environment. <https://doi.org/10.1016/j.atmosenv.2015.11.030>

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

**Table 45**

Gopalan, P., Jansen, P., and Batstone, D., 2013. Biochemical methane potential of beef feedlot manure: Impact of manure age and storage. Journal of Environmental Quality 42: 1205-12. <https://doi.org/10.2134/jeq2012.0457>.

**Table 46**

Bareha, Y., Affès, R., Buffet, J., and Girault, R., 2021. Sys-Metha: Outil de prediction des flux d’azote et de carbone sur les filières de méthanisation et des propriétés des digestats. Portail Data INRAE, V1. <https://doi.org/10.15454/U4S6OF>

Bradna, J., Malatak, J., Hajek, D. (2016). The properties of wheat straw combustion and use of fly ash as a soil amendment. Agronomy Research 14(4), 1257-1265. <https://agronomy.emu.ee/wp-content/uploads/2016/05/Vol14_nr4_Bradna.pdf>

Carabeo-Pérez, A., Odales-Bernal, L., Lopez-Davila, E, and Jimenez, J., 2021. Biomethane potential from herbivourous animal’s manures: Cuban case study. Journal of Materials Cycles and Waste Management 23, 1404-1411. <https://doi.org/10.1007/s10163-021-01220-9>

Dar, R.A., Parmar, M., Dar, E.A., Sani, R.K., and Phutela, U.G., 2021. Biomethanation of agricultural residues: Potential, limitations and possible solutions. Renewable and Sustainable Energy Reviews 135, 110217. <https://doi.org/10.1016/j.rser.2020.110217>

Fen, C., Gao, Y., Wei, L., Fenwu, L., Wuping, Z., Yushan, B., and Xiaomei, L., 2017. Maximal methane potential of different animal manures collected in northwest region in China. Int J Agric & Biol Eng, 2017; 10(1): 202－208. <https://ijabe.org/index.php/ijabe/article/view/2469/pdf>

Guérin, S., Azimi, S., Bernier, J., Rocher, V., Mottelet, S., and Pauss, A., 2016. Le pouvoir méthanogène des boues urbaines - Cartographie des boues de STEP et réduction du temps de mesure par un couplage « expérimentation en réacteur/modélisation ». Service public de l’assainissement francilien (SIAAP). <https://www.researchgate.net/publication/311815239_Le_pouvoir_methanogene_des_boues_urbaines_Cartographie_des_boues_de_STEP_et_reduction_du_temps_de_mesure_par_un_couplage_experimentation_en_reacteurmodelisation>

Hutnan, M., 2016. Maize silage as substrate for biogas production. Advances in Silage Production and Utilization, Eds.: da Silva, T., and Santos, E.M., IntechOpen. <https://doi.org/10.5772/64378>

Kargwal, R., Yadvika, Garg, M.K., Malik, K., Mehta, S., 2019. Effect of different concentration of paddy straw and cattle dung on biogas production. International Journal of Current Microbiology and Applied Sciences 8(7): 537-544. <https://doi.org/10.20546/ijcmas.2019.807.066>

Labatut, A., Largus, T., and Scott, N.R., (2011). Biochemical methane potential and biodegradability of complex organic substrates. Bioresource Technology 102, 2255-2264. <https://doi.org/10.1016/j.biortech.2010.10.035>

McGuire, T.A., Earle, F.R., Dutton, H.J. (1947). Determination of nitrogen in vegetable oils. The Journal oft the American Oil Chemists’ Society, November, 1947. <https://doi.org/10.1007/BF02643516>

Monch-Tegeder, M., Lemmer, A., Oechsner, H., and Jungbluth, H.O., 2013. Investigation of methane potential of horse manure. gricultural Engineering Journal: The CIGR e-journal 115(2), 161-172. <https://cigrjournal.org/index.php/Ejounral/article/view/2445/1736>

Ozbayram, E.G., and Ince, O., 2021. Comparative assessment of biogas potential of the most abundant agro-residues in Turkey. DEU Faculty of Engineering Journal of Science and Engineering, 23(68), 547-555. <https://doi.org/10.21205/deufmd.2021236817>

Pham, C.H., Triolo, J.M., Cu, T.T.T., Pedersen, L., and Sommer, S.G., 2013. Validation and recommendation of methods to measure biogas production potential of animal manure. Asian-Australas Journal of Animal Sciences 26(6), 864-873. <https://doi.org/10.5713/ajas.2012.12623>

Schumacher, B., Wedwitschka, H., Hofmann, J., Denysenko, V., Lorenz, H., and Liebetrau, J., 2014. Disintegration in the biogas sector – Technologies and effects. Bioresource Technology 168, 2 - 6. <https://doi.org/10.1016/j.biortech.2014.02.027>

**Table 47**

Guilayn, F., Jimenez, J., Rouez, M., Crest, M., and Patureau, D., 2019. Digestate mechanical separation: Efficiency profiles based on anaerobic digestion feedstock and equipment choice. Bioresource Technology 274, 180-189. <https://doi.org/10.1016/j.biortech.2018.11.090>

**Tables 61 & 62**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

# 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 C 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 and the amount of excreted C minus CH4 losses from manure deposited on pasture is used as an input to the IPCC Tier 2 and ICBM soil C models for the respective fields/pastures. The amount of N excreted minus direct and indirect N losses is used as manure inputs to the soil N pool for the respective soil N2O models.

### Manure C 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 livestock manure deposited on pasture

To estimate CH4 emissions from manure deposited on pasture (*CH4pasture*) for all animal groups, 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 located 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 EFs (*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-1 N 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 EF for manure 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-1 N 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, broilers and layers (**Eq. 4.2.1‑28**), other livestock (**Table 42**)

*EFdirect* Direct N2O-N EF 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

### NH3 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)

**Ammonia emissions from grazing beef and dairy cattle on pasture are calculated on a daily basis.**

**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 grazed pasture (enclosed, open range)

*T* Average outdoor daily temperature (°C)

**Eq. 5.4.1‑2**

where

*EFpasture\_adju* Adjusted NH3 EF for grazed pasture (kg NH3-N kg-1 TAN) (0 ≤ *EFpasture\_adju* ≤ 1)

*EFpasture* Default NH3 EF for grazed pasture (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

### NH3 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

**Indirect N2O emissions are calculated on a daily basis for all animal groups.**

For beef and dairy cattle, *Fracvolatilization* values for each animal group are calculated using **Eq. 5.4.3‑1**; 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. 5.4.3‑1** for beef and dairy cattle and derived from **Table 36** for all other animal groups

*EFvolatilization* EF for volatilization [kg N2O-N (kg NH3-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

**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

**Adjusted ammonia emissions from manure deposited on pasture are calculated on a daily basis.**

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

### Indirect N losses from manure deposited on pasture via leaching and runoff

**For all animal groups:**

**Eq. 5.4.4‑1**

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)

*FracNleach* Leaching fraction, calculated using **Eq. 2.6.6‑1**

*EFleach* EF 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 uses 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 (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, see **section 2.6.9.5**

## References

**5.2 Manure carbon**

Baron, V.S., Mapfume, E., Dick, A.C., Naeth, M.A., Okine, E.K., and Chanasyk, D.S., 2002. Grazing intensity impacts on pasture carbon and nitrogen flow. Journal of Range Management 55(6), 535-541.

**5.3 Direct N2O**

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

Lemke RL, Baron V, Iwaasa A, Farrell R, Schoenau J. 2012. Quantifying nitrous oxide emissions resulting from animal manure on pasture, range and paddock by grazing cattle in Canada. Final report submitted to the Greenhouse Gas Division, Environment Canada, by Agriculture and Agri-Food Canada, Saskatoon (SK).

Rochette, P., Chantigny, M. H., Ziadi, N., Angers, D. A., Bélanger, G., Charbonneau, É., Pellerin, D., Liang, C., and Bertrand, N., 2014. Soil nitrous oxide emissions after deposition of dairy cow excreta in eastern Canada. Journal of Environmental Quality, 43(3), 829– 841. <https://doi.org/10.2134/jeq2013.11.0474>

**5.4 Indirect N2O**

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 6**

See **section 2.8** for references

**Table 36**

See **section 4.10** for references

**Table 42**

See **section 4.10** for references

# Energy CO2 emissions

(by R. Kröbel, S.J. Pogue)

## Cropping emissions

Emissions estimates for each crop are calculated independently and results are reported for each crop/field separately. Cropping emission results are calculated on a yearly basis and prorated equally over the year (/12) for monthly reporting.

### CO2 from fuel use

These equations are used to calculate emissions from fuel use. Use **Eq. 6.1.1‑1** for cropped land, including annual crops and perennial forages, and **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). As a default, Holos uses 70 kg CO2 GJ-1 for *DieselConversion* (ECCC 2008).

#### Fallow land (Western Canada only)

**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 **Eq. 6.1.2‑1** for cropped land, including annual crops and perennial forages, and **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** for Western Canada, by region, soil type, tillage, crop type, in Eastern Canada use crop type based on **Table 52**)

*HerbicideConversion* Conversion of GJ for herbicide production to kg CO2 (kg CO2 GJ-1). As a 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 fertilizer production

These equations are used to calculate emissions from N, phosphorus (P) and potassium (K) fertilizer production. Use these equations for each fertilized crop, including annual crops, perennial forages and improved grassland/pasture.

#### CO2 from Nitrogen fertilizer production

**Eq. 6.1.3‑1**

**Eq. 6.1.3‑2**

where

*CO2Nfertilizer-upstream* CO2 emissions from N fertilizer production (kg CO2 year-1)

*CO2Nfertilizer-onfarm* CO2 emissions from N fertilizer application (kg CO2 year-1). **Note:** CO2 emissions associated with the application of urea and UAN fertilizers relate to C loss from the formulation itself, which is released shortly after application to soil, and do not account for any CO2 losses related to fuel consumption from the application of these fertilizers (Brentrup et al. 2018)

*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)**

#### CO2 from 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)**

#### CO2 from 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)

**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* EF (kg C (kg limestone)-1), a default EF of 0.12 for limestone is used (IPCC 2006,2019)

*44/12* C to CO2 conversion

### CO2 from irrigation

**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 irrigation applied[[13]](#footnote-14)

**Note:** 1.0 *mm irrigation* = 0.0394 *inches irrigation*

**Note:** 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

Emissions estimates are summed 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 and reported for each group separately.**

### CO2 from dairy

**This equation is used to calculate emissions for dairy production systems based on the number of lactating dairy cows.** This approach assumes zero energy emissions from other dairy animals, as the energy consumption relates to milking and milk refrigeration only.

**Eq. 6.2.1‑1**

where

*CO2dairy* Total CO2 emissions from dairy operations (kg CO2 year-1), by lactating cow group

*#cows* Number of lactating dairy cows

*DairyCowConversion* kWh per lactating dairy cow per year for electricity (kWh cow-1); as a default Holos uses 968 kWh cow-1 for *DairyCowConversion* (Vergé et al. 2007)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1); as a default Holos uses province-specific values for *ElectricityConversion* (kg CO2 kWh-1) (**Table 49**)

*#days* Number of days in month

### CO2 from swine

**This section calculates emissions for swine based on the number of animals in each animal group present on the simulated farm; results are reported for each animal group separately.**

**Eq. 6.2.2‑1**

**Eq. 6.2.2‑2**

**Eq. 6.2.2‑3**

**Eq. 6.2.2‑4**

**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

**Eq. 6.2.2‑6**

where

*CO2swine* Total CO2 emissions from swine operations (kg CO2 year-1), by animal group

*SwineConversion* kWh per pig per year for electricity (kWh pig-1); as a default Holos uses 1.06 kWh pig-1 for *SwineConversion* (Dyer and Desjardins 2006)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1); as a default Holos uses province-specific values for *ElectricityConversion* (kg CO2 kWh-1) (**Table 49**)

*#days* Number of days in month

### CO2 from poultry

**This section is used to calculate emissions for poultry based on the number of animals in each animal group present; results are reported for each animal group separately.**

**Eq. 6.2.3‑1**

**Eq. 6.2.3‑2**

where

*CO2poultry* Total CO2 emissions from poultry operations (kg CO2 year-1), by animal group

*barn\_capacity* Barn capacity (i.e., no. animals)

*PoultryConversion* kWh per poultry placement per year for electricity production (kWh poultry placement-1 year-1); as a default Holos uses 2.88 kWh poultry placement-1 year-1 for *PoultryConversion* (Dyer and Desjardins 2006)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1); as a default Holos uses province-specific values for *ElectricityConversion* (kg CO2 kWh-1) (**Table 49**)

*#days* Number of days in month

**Eq. 6.2.3‑3**

where

*CO2hatchery* CO2 emissions from direct energy inputs in hatchery operations (kg CO2 year-1), by animal group

*barn\_capacity* Barn capacity (i.e., no. eggs), by animal group

*223.52* kWh per 1,000 hatchlings produced (derived from a reported value of 804.68 MJ of energy for every 1,000 hatchlings produced (Pelletier 2017))

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1); as a default Holos uses province-specific values for *ElectricityConversion* (kg CO2 kWh-1) (**Table 49**)

**Note:** the *CO2hatchery* estimate represents the total CO2 emissions for an animal group (i.e., chicks (chicken eggs) or poults (turkey eggs)) for a single production cycle. To obtain a daily value, divide by the number of days in the production cycle (default values: 23 days for chicks and 30 days for poults).

### CO2 from housed beef

This section calculates emissions for housed beef cattle based on the number of cattle that are housed and the type of housing. Emissions are reported for the relevant beef cattle group in a ‘confined no barn (feedlot)’ or ‘housed in barn’ housing type.

**Eq. 6.2.4‑1**

where

*CO2housedbeef* Total CO2 emissions from housed beef operations (kg CO2 year-1), by animal group

*#animals* Number of housed cattle

*HousedBeefConversion* kWh per cattle per year for electricity (kWh beef-1 year-1); as a default Holos uses 65.7 kWh beef-1 for an annual *HousedBeefConversion* value (Dyer and Desjardins 2006)

*ElectricityConversion* Conversion of kWh of electricity to kg CO2 emissions (kg CO2 kWh-1); as a default Holos uses province-specific values for *ElectricityConversion* (kg CO2 kWh-1) (**Table 49**)

*#days* Number of days in month

## Manure spreading emissions

The manure spreading emissions for each animal group are calculated independently. In the Detailed Emissions Report, CO2 emissions associated with energy use during manure spreading are reported for each relevant field. Currently, in Holos V4, CO2 emissions from manure spreading are calculated for user-defined manure applcations only; emissions related to the default application of leftover manure will be implemented in a future version of Holos.

### Liquid manure spreading

**Eq. 6.3.1‑1**

where

*Volumelandmanure* Volume of liquid manure applied to land (1000 litres)

*Nlandmanure*(*liquid)(animalgrp)*Total N (kg) from land-applied liquid manure, by animal group and manure management system, 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 type and 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); as a default Holos uses 0.0248 GJ 1000 litre-1 for *LiquidManureConversion* (M. Wiens, La Broquerie project, University of Manitoba, personal communication)

*DieselConversion* Conversion of GJ of diesel to kg CO2 (kg CO2 GJ-1); as a default Holos uses 70 kg CO2 GJ-1 for *DieselConversion* (ECCC 2022).

**Eq. 6.3.1‑3**

where

*Total\_CO2liquidmanure* Total CO2 emissions from liquid manure spreading (kg CO2 year-1)

### Solid manure spreading

**Eq. 6.3.2‑1**

where

*Volumelandmanure* Volume of solid manure applied to land (1000 kg)

*Nlandmanure(solid)(animalgrp)* Total N (kg) from land-applied solid manure, by animal group and manure management system, calculated using **Eq. 4.5.2‑6** for solid beef and dairy manure, **Eq. 4.5.2‑16** for solid poultry manure and **Eq. 4.5.2‑22** for solid manure from all other livestock groups)

*Ncontent* N content of solid manure (% wet weight), by manure type and 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); as a default Holos uses 0.0248 GJ 1000 kg-1 for *SolidManureConversion* (M. Wiens, La Broquerie project, University of Manitoba, personal communication)

**Eq. 6.3.2‑3**

where

*Total\_CO2solidmanure* Total CO2 emissions from solid manure spreading (kg CO2 year-1)

## References

Dyer, J.A. and R.L. Desjardins. 2006. An integrated index of electrical energy use in Canadian agriculture with implications for greenhouse gas emissions. Biosystems Engineering 95 (3): 449-460. <https://doi.org/10.1016/j.biosystemseng.2006.07.013>

Dyer, J.A. and R.L. Desjardins. 2007. Energy based GHG emissions from Canadian agriculture. Journal of the Energy Institute 80(2): 93-95. <https://doi.org/10.1016/10.1179/174602207X187203>

ECCC, 2008. National Inventory Report 1990–2008: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4/2008E-PDF; ISSN: 1706-3353. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2022. National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the United Nations Framework Convention on Climate Change. Cat. No.: En81-4E-PDF; ISSN: 1910-7064; EC21275.02. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

NRC (Natural Resources Canada) 2008. Canadian ammonia producers : benchmarking energy efficiency and carbon dioxide emissions / prepared for the Canadian Fertilizer Institute and Natural Resources Canada. Published by the Canadian Industry Program for Energy Conservation. Cat. No. M144-155/2007E-PDF (Online). ISBN 978-0-662-46150-0

Pelletier, N., 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. Journal of Cleaner Production 152, 167-180. <https://doi.org/10.1016/j.jclepro.2017.03.050>

Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., and Worth, D., 2007. Greenhouse gas emissions from the Canadian dairy industry in 2001. Agricultural Systems 94 (3), 683-693. <https://doi.org/10.1016/j.agsy.2007.02.008>

**Table 6**

See **section 2.8** for references

**Table 48**

See **section 2.8** for references

**Table 49**

ECCC, 2008. National Inventory Report 1990–2006: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/2006E; ISSN: 1706-3353. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2009. National Inventory Report 1990–2007: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/2007E; ISSN: 1706-3353. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2011. National Inventory Report 1990–2009: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/2009E; ISSN: 1706-3353. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2012. National Inventory Report 1990–2010: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. ISSN: 1910-7064. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2013. National Inventory Report 1990–2011: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. ISSN: 1910-7064. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2014. National Inventory Report 1990–2012: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. ISSN: 1910-7064. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2015. National Inventory Report 1990–2013: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/2013E; ISSN: 1719-0487. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2017. National Inventory Report 1990–2015: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/1E-PDF; ISSN: 2371-1329. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2018. National Inventory Report 1990–2016: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/1E-PDF; ISSN: 2371-1329. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2019. National Inventory Report 1990–2017: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/1E-PDF; ISSN: 2371-1329. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

ECCC, 2020. National Inventory Report 1990–2018: Greenhouse Gas Sources and Sinks in Canada. Canada’s Submission to the UN Framework Convention on Climate Change. Cat. No.: En81-4/1E-PDF; ISSN: 1910-7064. Available at: <https://publications.gc.ca/site/eng/9.506002/publication.html>

**Tables 50 & 51**

Dyer, J., Desjardins, R., 2004. The Impact of Energy use in Canadian Agriculture on the Sector's Greenhouse Gas (GHG) Emissions. Research Branch, Agriculture and Agri-Food Canada, Technical Report, 17pp

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 liaised with departmental collaborators to circumvent this issue, but work on this is still ongoing and yet to be completed. One of the main challenges 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 emissions. Last but not least, the manner in which livestock economics is calculated is so different from how GHG emissions are calculated that we have no vision as of 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 and grasslands

## Trees

## Beef

## **Net return, contribution margin calculations and considerations**

# Summations

(by R. Kröbel)

This section outlines the equations used to sum emissions from all sources and to convert these emissions to CO2 equivalents (t CO2eq) based on their global warming potential (**Table 54**).

## N2O

### Direct soil N2O

**Eq. 8.1.1‑1**

where

*N2Odirectsoil*(*CO2eq*)Direct N2O emissions from soils (t CO2 eq year-1)

*N2Odirectsoil* Direct N2O emissions from soils (kg N2O year-1), calculated using **Eq. 2.6.9‑27**

*GlobalWarmingPotentialN2O* Global warming potential conversion factor for N2O (100 yr timeframe, IPCC 2015)

1000 Conversion from kg to t

### Indirect soil N2O

**Eq. 8.1.2‑1**

where

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (t CO2 eq year-1)

*N2Oindirectsoil* Indirect N2O emissions from soils (kg N2O year-1), calculated using **Eq. 2.6.9‑27**

### Direct manure N2O

**Eq. 8.1.3‑1**

where

*N2Odirectmanure*(*CO2eq*)Manure direct N2O emission from livestock (t CO2 eq year-1)

*Total\_N2Odirectmanure* Total manure direct N2O emission from livestock (kg N2O year-1), calculated using **Eq. 2.6.9‑27**

### Indirect manure N2O

**Eq. 8.1.4‑1**

where

*N2Oindirectmanure*(*CO2eq*)Manure indirect N2O emission from livestock (t CO2 eq year-1)

*Total\_N2Oindirectmanure* Total manure indirect N2O emission from livestock (kg N2O year-1), calculated using **Eq. 2.6.9‑27**

## Carbon

### Soil C

**Eq. 8.2.1‑1**

where

*ΔCO2soil*(*CO2eq*)CO2 emissions from soils (t CO2 eq year-1)

*ΔCO2e(soil)* CO2 emissions from soils (kg CO2 year-1), calculated using **Eq. 2.1.4‑2**

1000 Conversion from kg to t

### Shelterbelt and linear plantings C

**Eq. 8.2.2‑1**

where

*CO2shelterbelt*(*CO2eq*)CO2 emissions from tree plantings/shelterbelt (t CO2 eq year-1)

*Total\_CO2shelterbelt* Total CO2 emissions from tree plantings/shelterbelt (kg CO2 year-1), calculated using **Eq. 2.3.5‑2**

1000 Conversion from kg to t

### Energy CO2

**Eq. 8.2.3‑1**

where

*CO2energy*(*CO2eq*)CO2 emissions from energy use (t CO2 eq year-1)

*Total\_CO2energy* Total CO2 emissions from energy use (kg CO2 year-1), calculated using **Eq. 6.1.5‑1**

1000 Conversion from kg to t

### Enteric CH4

**Eq. 8.2.4‑1**

where

*CH4enteric*(*CO2eq*)Enteric CH4 emissions from livestock (t CO2 eq year-1)

*Total\_CH4enteric* Total enteric CH4 emissions from livestock (kg CH4 year-1)

*GlobalWarmingPotentialCH4* Global warming potential conversion factor for CH4 (100 yr timeframe, IPCC 2006)

1000 Conversion from kg to t

### Manure CH4

**Eq. 8.2.5‑1**

where

*CH4manure*(*CO2eq*)Manure CH4 emissions from livestock (t CO2 eq year-1)

*Total\_CH4manure* Total manure CH4 emissions from livestock (kg CH4 year-1)

1000 Conversion from kg to t

## Total emissions per farm

### Direct N2O – soils and manure

**Eq. 8.3.1‑1**

where

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (t CO2 eq year-1)

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (t CO2 eq year-1)

*N2Odirectmanure*(*CO2eq*)Manure direct N2O emissions from livestock (t CO2 eq year-1)

### Indirect N2O – soils and manure

**Eq. 8.3.2‑1**

where

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (t CO2 eq year-1)

*N2Oindirectsoil*(*CO2eq*)Indirect N2O emissions from soils (t CO2 eq year-1)

*N2Oindirectmanure*(*CO2eq*)Manure indirect N2O emissions from livestock (t CO2 eq year-1)

### CH4 – enteric and manure

**Eq. 8.3.3‑1**

where

*CH4* (*CO2eq*)CH4 emissions from the farm (t CO2 eq year-1)

*CH4enteric*(*CO2eq*)Enteric CH4 emissions from livestock (t CO2 eq year-1)

*CH4manure*(*CO2eq*)Manure CH4 emissions from livestock (t CO2 eq year-1)

### CO2

**Eq. 8.3.4‑1**

where

*CO2*(*CO2eq*)CO2 emissions from the farm (t CO2 eq year-1)

*CO2soil*(*CO2eq*)CO2 emissions from soils (t CO2 eq year-1)

*CO2shelterbelt*(*CO2eq*)CO2 emissions from tree plantings/shelterbelt (t CO2 eq year-1)

*CO2energy*(*CO2eq*)CO2 emissions from energy use (t CO2 eq year-1)

### Total farm emissions

**Eq. 8.3.5‑1**

where

*CO2eqfarm* Total annual farm CO2 eq emissions (t CO2 eq year-1)

*N2Odirect*(*CO2eq*)Direct N2O emissions from the farm (t CO2 eq year-1)

*N2Oindirect*(*CO2eq*)Indirect N2O emissions from farm (t CO2 eq year-1)

*N2Odirectmanure*(*CO2eq*)Manure direct N2O emission from livestock (t CO2 eq year-1)

## References

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

IPCC, 1990. Climate Change: The IPCC Scientific Assessment. Working Group 1 [Houghton, J.T., Jenkins, G.J., and Ephraums, J.J. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf>

IPCC, 1996. Climate Change 1995: The Science of Climate Change. Contribution of WG1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Meria Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_sar_wg_I_full_report.pdf>

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp. <https://www.ipcc.ch/report/ar3/wg1/>

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <https://www.ipcc.ch/report/ar4/wg1/>

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. <https://www.ipcc.ch/report/ar5/wg1/>

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, <https://doi.org/10.1017/9781009157896>. <https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/>

**Table 54**

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Edited by Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC. ISBN 4-88788-032-4. Available at: <https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>

# Expression of Uncertainty

(by R. Kröbel)

## Uncertainty associated with each emission category

Holos V4 will utilize the uncertainty estimates from V3 until better estimates can be developed. The previous estimates of uncertainty were developed based on expert opinion for each of the emission categories of emission reported by Holos (**Table 57**). The categorization system uses is provided in **Table 58**.

### Uncertainty estimate for net emissions

To determine the overall uncertainty for the estimate of net GHG emissions from a specified set of farm conditions, the following equation could be used in a future version of Holos:

**Eq. 9.1.1‑1**

where

*Uncertainty* Uncertainty associated with net farm emission estimate

*A* Emission estimate for each emissions category (t CO2equivalent – calculated in **Chapter 8**)

*a* Uncertainty estimate (**Table 58**, by uncertainty category associated with emission category and relative uncertainty in **Table 57**)

# Reporting

Holos model outputs are provided on the Results screen at different levels of detail and using different reporting methods. Outputs can be explored as CO2 equivalents (GHG emissions converted to CO2eq on the basis of their global warming potential) or as individual GHG amounts (in either kg or Mg/t) for each year of the simulation. Model outputs can be exported to Excel for further processing.

The **Detailed Emissions report** provides a summary of annual or monthly emissions, by field and animal group, as well as by emission source (Enteric CH4, Manure CH4, Direct N2O, Indirect N2O, Farm energy CO2 and Upstream CO2). Monthly estimates are provided either by summing daily emissions estimates (CH4), by equal subdivision (energy CO2), or by distribution table (N2O). Enteric CH4 derives primarily from ruminant livestock – note that enabling the ‘Show Additional Columns’ option also displays enteric CH4 estimates using an alternative calculation methodology. Manure CH4 is produced by liquid and solid manure, and depends on the manure management system. Direct N2O emissions derive primarily from the farm’s fields (from land-applied manure and synthetic fertilizers, as well as from crop residues and mineralization), but also from manure management systems – note that manure deposited directly on pasture by grazing animals is reported as part of the field emissions. Indirect N2O emissions result from manure and land management, and as for direct N2O, indirect N2O emissions associated with manure from grazing animals are reported on a field basis. Farm energy emissions relate to on-farm fuel use, while upstream CO2 emissions are associated with the off-farm production of fertilizers and pesticides. Although this last emission source is not part of the farm’s GHG budget, these emissions estimates are needed for C footprint assessments of specific commodities. Upstream CO2 emissions are available as annual estimates only. For a visual overview of GHG emissions from the simulated farm, for different GHGs and GHG sources, the user can view the **Emissions Pie Chart**, the **Component Emissions** chartand the **Overall Emissions** chart using the appropriate tabs on the Results screen.

The **Multiyear Carbon Modelling report** displays the outputs (in both grid and graph format) of the multi-year soil C model – either IPCC Tier 2 or ICBM. In the graph format, the annual soil C stock estimate for each field and year is displayed for the timeframe of the simulation – hovering with the mouse over any point on the graph will display the precise C stock estimate for the relevant crop and year. In the grid (or table) format, additional information on C fluxes and N losses for each field and year is available – these data can be exported to Excel for further processing.   
**Note:** the ‘Enable columns’ on the left-hand side of this window allows the user to choose which columns to display.

The **Manure Management report** allows the user to delve deeper into some of the model’s calculations by providing detailed data on feed intake, C and N excretion, as well as NH3 emissions from animal housing and manure management, and the amount of manure C and N available for application to land.

If the model user has added an anaerobic digestion component to their farm, the **Anaerobic Digestion** report will be visible on the Results screen. This report details the flows of substrate (and C, N, TAN, ON and VS) into the digester from all relevant sources, CH4/heat/electricity produced during the digestion process, and flows of digestate (and C, N, TAN, ON and VS) out of the digester at the end of the process. Following digestion, Holos as a default assumes that the digestate undergoes solid-liquid separation and is then stored before application to land; during this storage period, estimates of CH4 and N2O emissions are calculated. The user then has the option to apply the resulting digestate to land, after which all land-application related C and N losses are estimated using the same approaches used for land-applied manure.

For further exploration of the model outputs, Holos also provides an **Estimates of Production** report, which details the farm’s harvests, by field, crop and year, as well as the amount of manure N available for land application produced by each animal group and the amount of milk produced (if dairy cattle are present on the farm) or beef produced (if beef stockers & backgrounders and/or beef finishers are present on the farm). The **Feed Estimate Report** provides an overview of the feed intake for each animal group, on either a monthly or annual basis – a way to double-check the model inputs on livestock weight and average daily gain. Finally, the **Economics** report provides a general 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 farm management; instead, the user will have to change the cost estimates in the field/cropping systems component interface.

**Adjusting farm GHG estimates using soil C/CH4 to gas grid estimates:** If the user wishes to adjust their annual farm GHG emissions estimates to incorporate soil C sequestration estimates (where there is a gain rather than a loss of soil C), they can do so by subtracting the amount of C sequestered (converted into CO2 eq) from the total farm GHG emissions (CO2 eq). However, the user should note that when calculating an annual soil C sequestration rate, this can differ significantly depending on the simulation timeframe over which this value is calculated. We generally recommend to average C gains/losses where possible over multiple timeframes (e.g., 10 yrs, 20 yrs and 30 yrs), as they can differ significantly in the amount of soil C stored over time, and in some cases a gain may become a loss when assessed over a different timeframe. To adjust the farm GHG emissions to account for CH4 produced in an anaerobic digestion system that is input to the grid, the user can subtract the *CH4grid* value (calculated using **Eq. 4.8.2‑15**), but only when the gas grid contains natural (fossil) gas that is being replaced by this *CH4grid* amount.

# Appendices

(by A. W. Alemu, S.J. Pogue, P. Mantle, A. McPherson, and R. Kröbel)

## Residue removal and hay harvest

### 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 long-term storage more likely. The user is required to confirm the existence of a permanent storage structure, however, and unselecting the option will reduce the life span to 2 years.

**Note:** the equations in this section will be implemented in a future version of Holos.

**Eq. 11.1.2‑1**

**Eq. 11.1.2‑2**

where

*Storagestraw/haybales* Number of bales available on-farm

## Bedding application rate calculator

### User-required inputs

For each management period **(# of days, # of animals known**):

* no. of days bedding is applied
* per each application (one single input per management period):
  + total # of bales used
  + specification whether bales were imported (yes/no) from outside the farm – **Note:** this will be implemented in a future version of Holos
    - 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

### 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 (%), user-defined

**Eq. 11.2.2‑2**

**Eq. 11.2.2‑3**

where

*#daysManagementPeriod* User-specified length of management period (no. of days)

*#daysapplication frequency* User-specified application frequency (no. of days)

*BeddingMaterialapplied* Total bedding applied (kg)

*Beddingapplied(day)* Total bedding applied per day (kg day-1)

*Beddingapplied(rate)* Total bedding applied per animal per day (kg head-1 day-1)

## Feed requirement balance

### Dry matter intake and forage requirement

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**

where

*DMIanimal(day)* DM intake per animal per day (kg head-1 day-1)

*GEI animal(day)*  Gross energy intake per animal per day (MJ head-1 day-1) calculated in **Eq. 3.1.1‑11** (beef cattle), **Eq. 3.2.1‑10** (dairy cattle) and **Eq. 3.3.1‑13** (sheep)

*18.45* Conversion factor for gross energy per kg of DM (MJ kg-1)

*DMIanimalgroup(day)* DM intake per animal group per 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 (#animals)

*#daysManagementPeriod* User-specified length of management period (#days)

**Eq. 11.3.1‑4**

where

*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 in 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 per day (kg head-1 day-1)

*FinalWeight* Final animal weight (kg)

*BWintakelimit* Body weight intake limit – this is 0.0225 (2.25%) for beef cattle and 0.040 (4%) for dairy cattle

**If the calculated DMI fulfills the following condition:**

**Eq. 11.3.1‑6**

Users will be reminded to review whether they are providing the animals with a diet that fulfills their daily energy requirements.

**Feed N use efficiency**

This calculation needs to be completed for each animal group for beef and dairy cattle per month, excluding calves.

**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 using **Eq. 4.2.1‑1** for beef and dairy cattle.

**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** (beef calves), while for dairy calves a constant value of 0.078 kg N head-1 day-1 is used. *Nexcretion\_rate* for sheep is estimated 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. 11.3.2‑7** and *CptoSoil(t)*using **Eq. 11.3.2‑8**. 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*, *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 forage C consumed by livestock in year *t*.

Where there are multiple animal groups (e.g., beef cows, beef bulls, beef heifers) grazing on field *n* in year *t* (either for one or more grazing management periods), the equations below are calculated for each animal group separately and the *Yield* and *CptoSoil* estimates are summed on a field basis for the year.

**Note:** these calculations only apply to major livestock types for which we have DMI estimates (i.e., beef cattle, dairy cattle, sheep and swine).

**Eq. 11.3.2‑1**

**Eq. 11.3.2‑2**

**Eq. 11.3.2‑3**

where

*Carbon UptakePasture(group, period, field n)* Amount of C foraged from field *n*, by animal group and management period

*Carbon UptakePasture(period, field n)*Amount of C foraged from field *n* by all animal groups during a specific management period

*Carbon UptakePasture(field n)*Total amount of C foraged per year from field *n* (kg C)

*Carbon Exporthay(field n)*Total amount of C exported as baled hay per year from field *n* (kg C)

*DryMatter(straw/hay)* DM (kg DMbale-1)

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

**For a single grazing period on field *n* in year *t*:**

When there is only one 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**

**Eq. 11.3.2‑5**

**For multiple grazing periods on field *n* in year *t*:**

When there are two or more grazing management periods on field *n* in year *t*, *Cp(t)* for the final management period is calculated using **Eq. 11.3.2‑4** (considering the C in leftover forage at the end of the last grazing period of the year), while *Cp(t)* for all preceding grazing periods is calculated using **Eq. 11.3.2‑6** (which does not consider leftover forage at the end of these non-final grazing periods):

**Eq. 11.3.2‑6**

**Eq. 11.3.2‑7**

where

*Carbon UptakePasture(group, period, field n)* Amount of C foraged from field *n*, by animal group and management period

*Carbon Exporthay(field n)*Total amount of C exported as baled hay per year from field *n* (kg C)

*Cp(t,period\_final)* 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\_beforefinal)* 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,period)* Total annual plant C in agricultural product for field *n* (kg ha-1), calculated using **Eq. 11.3.2‑7**

*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 (%)

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

**For all grazing scenarios:**

**Eq. 11.3.2‑8**

**Eq. 11.3.2‑9**

where

*Carbon UptakePasture(group, period, field n)* Amount of C foraged from field *n*, by animal group and management period

*Carbon UptakePasture(period, field n)*Amount of C foraged (field *n*) by all animal groups during a specific management period

*Carbon UptakePasture(field n)*Total amount of C foraged per year from field *n* (kg C)

*Carbon Exporthay(field n)*Total amount of C exported as baled hay per year from field *n* (kg C)

*Cp(t,period\_final)* 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\_beforefinal)* 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,period)* Total annual plant C in agricultural product for field *n* (kg ha-1), calculated using **Eq. 11.3.2‑4**/**Eq. 11.3.2‑5**/**Eq. 11.3.2‑6**/**Eq. 11.3.2‑7**

*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 (%)

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

*YieldPasture(t)* Total aboveground biomass yield for field *n* in year *t* (kg DM ha-1)

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

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

## Estimates of production output equations

### 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 per 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 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 per 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 are 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 are 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 the 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)

## Terminology

### Emission sources

**Soil N2O– direct:** direct emissions of N2O from N supplied to soil, in the form of synthetic or organic N (the latter includes 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 during the housing and manure storage stages, as well as upon application to land

**Manure N2O – direct:** emissions of N2O from manure handling during the housing and manure storage stages, as well as upon application to land

**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:** CO2 emissions from on-farm machinery use (fuel consumption), as well as the use of pumps (irrigation)

**Upstream emissions:** the sum of emissions associated with the production of inputs (i.e., synthetic fertilizer and pesticides).

### Farm components

This refers to each specific farm operation, based on product or output. For example:

**Land managment**

* Field
* Crop rotation
* Shelterbelt

**Beef**

* Beef Cow-Calf
* Beef Stockers and Backgrounders
* Beef Finishers

**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- or underestimated depending on the starting SOC value and the length of the simulation period

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 4.10** for references

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Myra Martel (University of Saskatchewan) – water balance model development

Elwin Smith (formerly AAFC) – data provision (fuel energy requirement estimates for crops in Western Canada)

**Holos Research & V3**

Karen Beauchemin (formerly AAFC) – model development (beef and dairy model)

Shannan Little (AAFC) – model development

Ken McLean (formerly AAFC) – software development

Bobbi Helgason

**Holos Classic:**

Henry Janzen (formerly AAFC) - model development

Julia Lindeman

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 *Carbonconcentration* value of 0.45 kg C kg-1 plant biomass is derived from Baron et al. (2002) for mixed pasture. This value is 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 the estimation of dead organic matter. Compilers should apply the dead organic matter methods in **section 5.2.2** of IPCC (2019). [↑](#footnote-ref-8)
8. The *Carbonconcentration* 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)”. For Holos, a default value of 25% reduction in manure CH4 emissions for systems with a solid cover has been assumed. [↑](#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. (%, DM basis) = 48.95%; for microsieve (MS) sludge: C conc. (%, DM basis) = 47.60%; average C conc. = 48.3% or 0.483 kg kg-1 DM. From Serbanescu et al. (2017): average C conc. = 27.6% or 0.276 kg kg-1 DM. Average across all studies = 41.1% or 0.414 kg kg-1 DM. [↑](#footnote-ref-13)
13. 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 (ECCC 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 ECCC (2022): electricity – 0.200 kg CO2 kWh-1 (Table A13-1 of ECCC (2022)); natural gas = 13.80 t C TJ-1 (Table A4-2 of ECCC (2022)). [↑](#footnote-ref-14)