CIBUSmod 25.04: A spatially disaggregated biophysical agri-food systems model for studying national-level demand- and production-side intervention scenarios

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Abstract. CIBUSmod 25.04 is an open-source, spatially disaggregated biophysical model designed to evaluate resource use and environmental impacts in agri-food systems on national and sub-national level under varying production and demand scenarios. Developed within the Swedish Mistra Food Futures programme, CIBUSmod provides a flexible, modular framework for assessing food systems sustainability. It can integrate regionalised data on crop production, livestock systems and land use at arbitrary spatial resolution. In the model agricultural production is distributed regionally to meet an exogenous demand, while enforcing agronomic and biophysical constraints. Using Sweden as a case study, the model's application is demonstrated by constructing and validating a baseline and conducting a scenario analysis. The results highlight CIBUSmod's ability to quantify trade-offs in land use, nutrient flows, and greenhouse gas emissions across different transition pathways. The model is designed to be accessible, utilising Python and Jupyter Notebooks with Excel-based input data management. It is publicly available under the GNU GPLv3 licence. By enhancing transparency and usability in food systems modelling, CIBUSmod serves as a valuable tool for researchers to explore sustainable agri-food systems transitions at national and sub-national scales.

1 Introduction

Scenario analysis is a valuable tool for studying different visions for future food systems, and identify synergies and trade-offs that can guide policy decisions. To quantitatively assess scenarios of our future food systems, numerous system models have been developed, varying in scope, levels of detail, and complexity.

On a global level, integrated assessment models (IAMs) such as GLOBIOM (IBF-IIASA 2023) and MAgPIE (Dietrich *et al.* 2019) have been extensively used to study effects on land use and greenhouse gas emissions under different Shared Socioeconomic Pathways (SSPs), feeding into multiple IPCC assessments. However, such models have been criticised for being opaque (Rosen 2015) and inaccessible to large groups of researchers and practitioners (Jones *et al.* 2023). As a response to this, simpler biophysical mass flow models such as BioBaM-GHG (Kalt *et al.* 2021), SOLm (Muller *et al.* 2017; Müller

30 2020) and CiFoS (van Selm *et al.* 2022; Simon *et al.* 2024) have been developed and used to study the biophysical feasibility of different future scenarios. Unlike IAMs, where supply and demand are calculated endogenously through economic modelling, based on price elasticities, these models determine demand from user input or by optimising diets to meet nutritional needs. Some of these models also allow the creation of large numbers of scenarios and scenario combinations to explore 'biophysical option spaces' (Muller *et al.* 2017; Kalt *et al.* 2021). This could be the space of combined assumptions on future

35 diets, productivity, land use, and more, that are biophysically feasible under different constraints.

For the purpose of national decision-making, however, these global-, or larger regional-scope models are not always adequate as they do not account for local nuances, policy priorities and knowledge. There is therefore a need for flexible models that can account for such local specifics. Recognizing this, the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) consortium (Jones *et al.* 2023) has engaged researchers from diverse countries to develop national land-use and food systems

40 pathways in collaboration with local stakeholders. These pathways are then globally aligned by balancing imports and exports iteratively, allowing for integration of local priorities alongside global food system sustainability goals. However, because the 'FABLE Calculator' used for assessing country pathways operates at an aggregated national level, it cannot directly evaluate scenario feasibility or environmental impacts on sub-national levels (Jones *et al.* 2023).

There is a lack of flexible, open-source, spatially disaggregated modelling frameworks that operate nationally and sub-

45 nationally with a comprehensive food systems perspective. To address this, CIBUSmod is introduced, a relatively light-weight biophysical food systems modelling framework developed within the Swedish Mistra Food Futures program, designed to incorporate detailed sub-national data and knowledge. It enables the evaluation of land use, material flows, and environmental impacts under different future food systems scenarios. Using Sweden as a case study, its applicability is demonstrated through data acquisition, validation, and scenario assessment. The model, CIBUSmod 25.04, was built in Python and is made available

50 as open-source under the GNU GPLv3 licence.

This paper is intended to act as a source of reference for future work as well as an introduction for new users. In section 2, a description of CIBUSmod's general structure and different modules is provided. In section 3, a use case example for Sweden is provided, describing data acquisition and model validation as well as providing an example of scenario simulation and assessment. Finally, in section 4, the model's applicability and plans for future development are discussed. In addition, the

55 public GitHub repository contains a user's guide that focus on the technical aspects of installing, setting up the Python environment, structuring input data, and setting up model runs.

2   Model description

CIBUSmod satisfies an exogenous national demand for crop and animal products (including exported products) with domestic agricultural production by distributing crop areas and animals over a number of user-defined sub-national regions. This enables

60 the use of sub-national data of arbitrary geographic resolution. The distribution of crop areas and livestock numbers across regions is determined by solving a convex optimisation problem, which minimises deviation from a pre-defined initial state

(e.g., the current distribution), while also enforcing constraints to ensure that the solutions are biophysically and agronomically feasible.

A key module of the model is the *ParameterRetriever*, which provides a flexible way to input data at different levels of

65 specificity depending on availability, with the model automatically using the most specific data provided. This could range from national average values to region-specific values that differ by crop/animal, production system (e.g. organic and conventional), etc. All input parameters are provided through Excel workbooks, making the model easy to use without extensive programming knowledge. It allows users to add and parameterise additional food items, crops, and livestock production systems, to be able to address diverse research questions. Parameters are categorised into 'default parameters',

70 which include the initial values required to run the model, and 'scenario parameters', which describe how these default values are expected to change over time under different scenarios. When designing scenarios, only parameters expected to change need to be specified. Unspecified parameters make use of their default values.

CIBUSmod uses primarily open-source Python packages and is ideally run via *Jupyter Notebooks*. This facilitates the documentation of model runs and the generation of output figures in a convenient and reproducible way. Output data is stored

75 in an SQLite database, and the modelling framework provides tools for extracting, summarising, and visualising the model outputs.

The framework is modular, with independent components handling different parts of the calculations, which simplifies maintenance and allows for the incorporation of additional functionality by adding new modules. The modules are organised into 'main modules', which store all model output, and 'management (mgmt) modules' that perform specific calculations

80 without storing output data. Figure 1 provides an overview of the CIBUSmod modelling framework and its included modules.
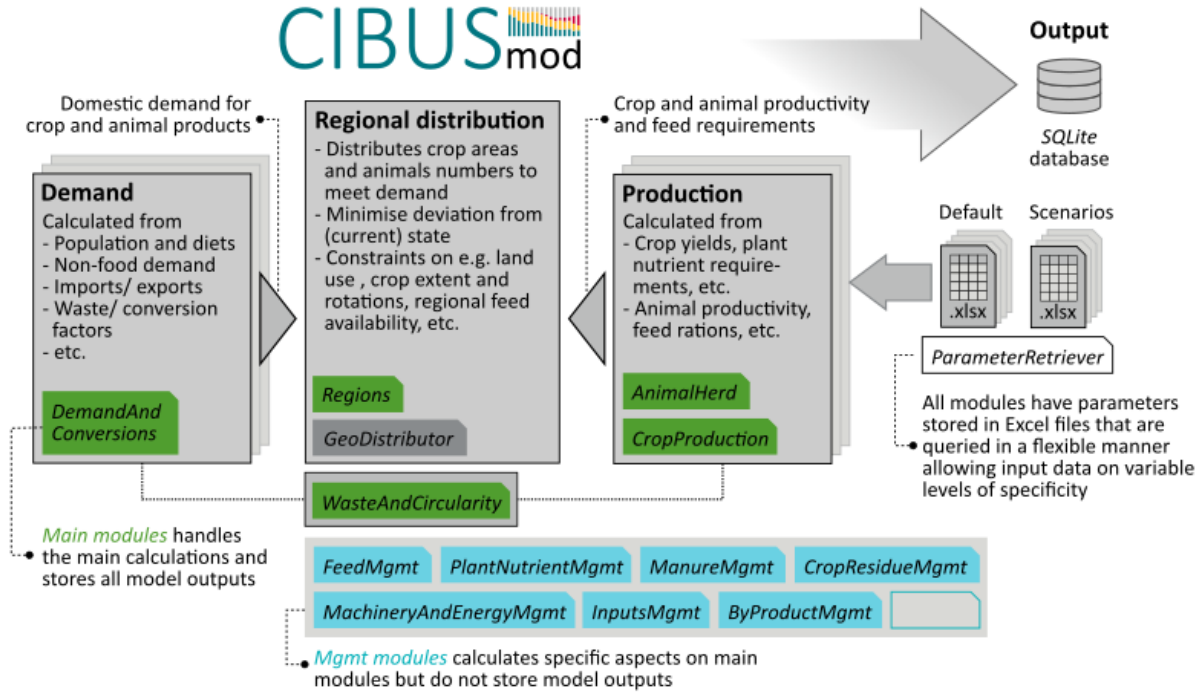
Figure 1. Schematic illustration of CIBUSmod model structure showing the calculation flow from accessing input data via the ParameterRetriever (right hand side) through calculating demand and production in the main modules (green boxes), and regional distribution via the GeoDistributor module (grey box)

85 The following sections describe all main components of the modelling framework and provide details on the steps involved in the different calculations.

2.1 Regional distribution of crop areas and animal numbers

Distribution of crop areas and animal numbers across regions is handled by the *GeoDistributor* module. In the default case, crop areas and animal numbers are distributed by solving a quadratic optimisation problem with the goal function in Eq. (1):

90 $$min \sum \left(f_{i,j} x_{i,j} - f_{i,j} x0_{i,j}\right)^2,$$ (1)

where $x_{i,j}$ and $x0_{i,j}$ is the area or number of crop or animal i in region j of the solution and the initial state, respectively. The factor $f_{i,j}$ is calculated from Eq. (2):

$$f_{i,j} = rn_{i,j} \times sf_{i,j},$$ (2)

where $rn_{i,j}$ is a factor that normalises all features (i.e. distinct land use classes and animal species) based on the maximum $x0$

95 of each feature. The scaling factor $sf_{i,j}$ is calculated from Eq. (3):

$$sf_{i,j} = \left(\frac{\overline{x0}}{x0_{i,j}}\right)^{sp},$$ (3)

where sp is a parameter that controls the power of scaling; $sp = 0$ means that the model aims to minimise deviation from the initial state in absolute terms. A larger sp gives increasing weight to relative deviations. Thus, a larger sp will result in larger absolute changes for crops, animals and regions where areas and animal numbers are large in the initial state. This scaling

100   factor is introduced to give less dramatic changes in smaller regions. For example, in the case of a scenario where demand for a specific crop is reduced, $sp = 0$ may result in areas going to zero in regions where that crop is grown on a small area in the initial state (i.e. result in a 100% relative reduction). Increasing sp will penalise these relative deviations, which will result in larger absolute deviations in large regions while maintaining areas in the smaller regions. The selection of sp is an arbitrary choice that has to be made by assessing the plausibility of resulting land use patterns. In the model runs presented in this paper

105    $sp = 0.4$ is used throughout.

It is also possible to supply a custom goal function as long as the problem remains convex. This allows users to study scenarios where, for example, land use is minimised or certain output from the system are maximised.

The optimisation problem is solved with the Python package *cvxpy* (Diamond & Boyd 2016), using *Gurobi* (Gurobi Optimization LLC 2024) as the backend solver. The problem is solved under a number of constraints, summarised in Table 1.

110   These constraints ensures biophysically and agronomically plausible solutions and allow for flexibility in deciding which constraints to include in a model run. It is also possible to manually constrain solutions depending on specific research questions.

Apart from the built-in constraints listed in Table 1 it is also possible to programmatically specify additional constraints without changing the main code of the model as long as the problem remains convex.

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Table 1. Summary of constraints included in GeoDistributor module that distributes crop areas and animal numbers across regions in CIBUSmod.

Constraint	Description
C1. Production meets demand	Crop areas and animal numbers must meet demand for crop and animal products, including feed demand.
C2. Regional feeds	For specified feeds the share produced within the same region as the consuming animals must exceed a threshold. This constraint is used to e.g. ensure regional supply of grazing and roughage.
C3. Max land use	Land use per land use class (e.g. cropland, semi-natural grasslands) may not exceed a threshold, specified as a multiple of land use in the initial state.
C4. Max share in animal sub-system	The number of animals in user-defined sub-systems (see section 2.4) may not exceed a specified share of total animals in that species, breed and production system.
C5. Max share of crop in feed	User-defined crop groups may not supply more than a specified share of a certain feed. This constraint is used to e.g. limit the share of semi-natural grasslands in total grazing.
C6. Crop rotations	The area of cropland devoted to user-defined crop groups (e.g. grain legumes, brassicaceae) are constrained to a specified minimum and/or maximum share of cropland in any given region and production system.
C7. Climate suitability of crops	Crops may only be grown in regions where the number of growing degree days exceeds a threshold defined per crop.
C8. Flexible constraint	Flexible constraint that constrains any given variable in the model to user-defined values. Allows specification of equality, minimum and maximum constraints.
C9. Flexible constraint	Flexible constraint that constrains the sum of given variables to user-defined values. Allows specification of equality, minimum and maximum constraints.

2.2 Calculation of demand for agricultural production

Demand for agricultural production is handled with the *DemandAndConversions* module, which takes exogenous inputs of
120 population size, national diets (including import shares and shares of food from different production systems such as organic or conventional agriculture) and demand for non-food and export uses. Diets are supplied in terms of food consumed (i.e. after accounting for all losses), which allows for assessing nutritional adequacy of supplied diets. The model uses supplied waste generation and conversion factors to calculate total national demand for crop and animal products, by-products and crop residues as well as generated by-products, wastes and import demand.

125 For dairy products, the model balances the supply and demand for dairy fats. This is done by adding exports of low-fat (skimmed) milk powder if demand for domestically produced high-fat dairy products, such as butter and cream, leads to a higher demand for dairy fats than that generated by domestically produced low-fat dairy products.

In the current version of the model, the supply and demand for by-products is balanced in the *ByProductMgmt* module by adding additional imports of by-products if domestic supply does not meet demand for feed, food and non-food uses. Surplus

130 by-products are either assumed to be exported or transferred to waste management (see section 2.9), or a mix thereof, as specified through input parameters.

2.3 Crop production systems

Crop production is handled with the *CropProduction* module, which calculates the mass of harvested crop products generated from cultivating a crop on a given area. Each production unit is specified by a crop, production system (e.g., conventional or

135 organic), and region. The model allows for parametrising multiple crops (e.g. winter and spring wheat) used to produce the same product as well as a single crop used to produce multiple products (i.e. to represent intercropping). The main input to this module is crop yields, but it also takes input parameters for seeding density, above and below ground crop residues, crop nutrient contents, etc. This module allows specifying the maximum share of cropland that can be devoted to specific groups of crops in crop rotations, as well as the climatic requirements of different crops in terms of minimum number of growing

140 degree days needed for a crop to be cultivated in a region. These parameters are used in the *GeoDistributor* (see section 2.1) to constrain the regional distribution of crop areas.

2.4 Livestock production systems

Livestock production is managed through separate modules for each species and in some cases breed (

Table 2). Each production unit is defined by a species, breed, production system, sub-system, and region, allowing for
parameter settings at this specific level, or at a more general level. The 'production system' attribute (e.g., conventional or
organic) plays a central role in linking livestock product demand and feed supply. All feed for a given livestock unit must
come from crops or by-products produced within the same production system. Similarly, the livestock products—such as milk,
meat, or eggs—produced are used to meet the demand for foods from the same production system. The use of different sub-
systems (e.g. ley or maize silage based dairy production or winter or spring lamb production) allows for further refinement,
such as different rearing and feeding strategies or productivity within the same overall production system.

For each livestock production unit, the average number of live animals in a year, culled/lost animals, and the production of
livestock products, are calculated based on parameters such as live weight gains, fertility, milk or egg yields, recruitment rates,
mortality at different stages, and slaughter ages.

155 **Table 2. Overview of livestock production modules and methods used to calculate feed requirements, manure excretion and enteric methane emissions**

Species (breed)	Animal categories	Module name	Feed requirements	Manure excretion		Enteric methane
				VS	N, P, K	
Cattle	cows, breeding bulls, suckling calves, calves for slaughter, heifer calves, steer calves, bull calves, heifers, steers, bulls	*CattleHerd*	ME requirements (Spörndly 2003)	Energy balance	Mass balance	Gross energy intake, methane conversion factor from feed ration
Sheep	ewes, rams, lambs	*SheepHerd*	kg DM per head	"	kg N/P/K per head	Gross energy intake, fixed methane conversion factor
Horses	broodmares, young horses, low-performing horses, medium-performing horses	*HorseHerd*	ME requirements (Jansson 2013)	"	"	kg CH_4 per head
Pigs	sows, boars, piglets, gilts, growing pigs, finishing pigs	*PigHerd*	NE requirements (Simonsson 2006; Göransson & Lindberg 2011)	"	Mass balance	kg CH_4 per head
Poultry (layer)	breeding hens and roosters, laying chicks, laying hens (16-28 weeks), laying hens (29-59 weeks), laying hens (>59 weeks)	*LayerHerd*	kg DM per head	"	kg N/P/K per head	kg CH_4 per head
Poultry (broiler)	breeding hens, breeding roosters, broilers	*BroilerHerd*	kg DM per weight gain (broilers) or head (parents)	"	"	kg CH_4 per head

ME = metabolizable energy, DM = dry matter, VS = volatile solids, N = nitrogen, P = phosphorus, K = potassium

2.4.1 Feed requirements and rations

Feed requirements, in terms of dry matter feed intake, are calculated per animal based on either energy requirements, feed
160 conversion ratios or a fixed dry matter feed intake per head. For cattle and horses metabolizable energy intakes are calculated
based on the methods presented in Spörndly (2003) and Jansson (2013), respectively. For sheep, feed intake is calculated from
fixed factors for dry matter intake per slaughtered head of lambs or per head and year for other sheep. For pigs, net energy
intakes are calculated based on the methods presented in Simonsson (2006) and Göransson and Lindberg (2011). For poultry,

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fixed factors for dry matter intake per head and year are used for laying hens and parent animals while for broilers feed

165 conversion ratios (kg dry matter (DM) feed/kg live weight gain) are used to calculate feed intake.

Intakes of different feeds are then calculated in the *FeedMgmt* module based on exogenously supplied feed rations, expressed in terms of share of dry matter intake supplied from different feeds over a year, along with parameters for the energy density of different feeds. This module also calculates the nitrogen (N), phosphorus (P), and potassium (K) contents of the feed as well as enteric methane emissions.

170 Finally, feed intakes are translated to demand for domestic and imported crop and by-products using parameters for import shares as well as storage and feeding losses. Domestic crop product demand is handled in the *GeoDistributor* module during the balancing of demand and production (see section 2.1). Parameters can also be supplied to enforce that a minimum share of demand for certain feed crops are supplied from within the same sub-national region as the consuming animals to e.g. ensure that there is regional supply of roughages.

175 **2.4.2   Enteric methane emissions**

For cattle and sheep, enteric methane emissions are calculated based on gross energy intake and methane conversion factors. For sheep, fixed methane conversion factors are used, analogous to the Tier 2 methodology presented in IPCC (2019), while for cattle, methane conversion factors are calculated based on feed ration composition according to the methodology presented in Bertilsson (2016), representing a Tier 3 methodology. For other livestock species, enteric methane emissions are calculated

180 from fixed emissions factors per head as in the Tier 1 methodology in IPCC (2019).

2.5   Manure management

Calculation of manure generation and losses are handled within the *ManureMgmt* module.
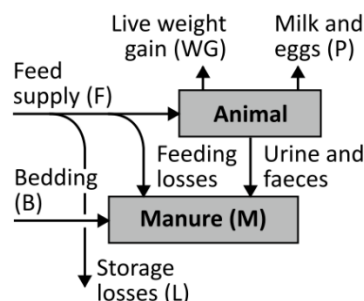
2.5.1   Manure excretion

Excretion of volatile solids (VS) in manure are calculated through an energy-balance approach using Eq. (4), which is based

185 on the Tier 2 method in IPCC (2019), together with total DM feed intake per animal (section 2.4.1) and parameters on gross energy (GE) and digestible energy (DE) contents of the different feeds.

$$VS = [GE - (DE + GE \times f_{UE})] \cdot \left(\frac{1 - ASH_{rat}}{GE_{rat}}\right), \tag{4}$$

where VS is volatile solids excretion per animal (kg head^{-1} year^{-1}), GE is gross energy intake from feeds (MJ head^{-1} year^{-1}), DE is digestible energy intake (MJ head^{-1} year^{-1}), f_{UE} is the fraction of urinary energy of GE intake (set to 0.04 for ruminants

190 and horses; 0.02 for pigs), ASH_{rat} is the share of ash in the feed ration (kg kg DM^{-1}), and GE_{rat} is the gross energy in the feed ration (MJ kg DM^{-1}).

For poultry, apparent metabolizable energy intake from feeds (AME; MJ head^{-1} year^{-1}) are used instead of $(DE + GE \times f_{UE})$ in equation (4). This directly represents the gross energy in feeds minus energy in faeces and urine (Abdollahi *et al.* 2021).

Figure 2. Schematic illustration of mass-balance for calculating nitrogen (N), phosphorus (P) and potassium (K) excretion in manure. N/P/K excretion is given by the equation M = F + B – L – WG – P

Excretion of N, P and K are estimated from either: fixed excretion factors per head and year in line with the Tier 1 or 2 methodology in IPCC (2019), or from a mass-balance-calculation based on the methodology described in Statistics Netherlands (2012). The mass balance approach (Figure 2) is used for livestock modules that explicitly calculates live weight gains for each animal category, which currently include cattle and pigs. Excretion of N, P and K in manure is then calculated by summing inputs in the form of feed and bedding materials and subtracting outputs and losses in the form of feed storage losses, live weight gains and livestock products (i.e. milk and eggs). Nutrient contents of feed supply is calculated in the *FeedMgmt* module (section 2.4.1) and nutrient concentrations in live weight gain for different animal categories and livestock products are supplied as parameters.

2.5.2   Storage emissions and losses

After calculating manure excretion, parameters are used to fractionate the generated manure from each livestock production unit across different manure management systems (e.g. liquid manure, solid manure, and deep litter) with distinct parameters for calculating losses in stables, storage, and during application.

Losses of methane (CH_4) during manure storage are calculated from VS in excreted manure (section 2.5.1) and specified methane conversion potentials (B_0) and methane conversion factors (MCF) as per the IPCC (2019) Tier 2 methodology for all livestock categories. Total carbon (C) losses are calculated based on the C content in manure VS and a C loss factor, both of which are supplied as parameters. All parameters can differ across animal categories and manure management systems. The difference between total C losses and CH_4-C losses are assumed to be carbon dioxide (CO_2).

The calculation of N, P and K losses is performed by applying loss factors, representing the proportion of each element lost in stables and during storage. This approximately corresponds to the Tier 2 methodology for manure management in the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency 2023). However, an explicit balance for total ammoniacal nitrogen (TAN) is not implemented. Loss factors can be specified per emitted compound, manure management system, animal type, etc. For N, factors can be specified either as a share of total N or TAN, depending on available data.

220   After determining all losses, these are subtracted from the excreted amounts to calculate the remaining C, N, P and K in the manure that is available for spreading on fields. This mass-balance approach ensures that nutrient availability for agricultural use is accurately modelled, reflecting different management practices and loss processes.

2.6   Plant nutrient management and liming

Calculation of N, P and K requirements for different crops as well as distribution of available animal manure and other
225   fertilisers are handled with the *PlantNutrientMgmt* module. This module also calculates lime requirements and application, as well as nutrient emissions into the environment from fertiliser, manure and lime application, soil processes and leaching.

2.6.1   Crop nutrient requirements

Crop N input requirements are calculated in terms of kg plant available N per hectare from a second order polynomial equation, using the crop yield in tonnes per hectare as a variable and coefficients that can be specified per crop, production system,
230   region, etc. Data for deciding the equation coefficients are e.g. national fertiliser recommendations and depending on data availability some coefficients may be set to zero to model requirements from a linear function of yield or as a fixed per hectare requirement. After calculating the requirements, these are met through a combination of residual N from crops (i.e. N released to consecutive crops in rotation) and application of manure and other fertilisers (see section 2.6.2). The amount of residual N from crops is given as parameters in terms of kg residual N per hectare for different crops. As such, N fixation is not explicitly
235   modelled in the current version but is indirectly accounted for in setting parameters for N requirements and residual N, making it possible to e.g. model green manure crops.

Crop P and K input requirements are calculated in a similar fashion as N requirements but only allow for a linear relationship with yield. Requirements can also depend on the stocks of P or K in the soil which can be specified per region. P and K requirements also allow for specifying an adjustment factor to account for e.g. uneven distribution of manure and intra-regional
240   variation in soil P/K stocks, leading to regional over-application compared to the requirements estimated from fertiliser recommendations.

2.6.2   Allocation of manure and other fertilisers

To quantify manure application and mineral fertiliser requirements, plant nutrients (N, P and K) in manure available for spreading are calculated as described in section 2.5. A stepwise procedure is then used to distribute manure across crop areas.
245   First (1), manure deposited while grazing is distributed based on the share of grazed biomass from different crops. Then (2), manure produced in organic animal production systems is distributed to organic crop areas within each region, based on plant available N requirements (see section 2.6.1). For manure and other organic fertilisers, the plant available fraction of N is assumed equal to the TAN fraction. Then (3), manure produced in conventional animal production systems is distributed to organic areas within the same region it is produced, up to a maximum share of plant available N requirements, reflecting the
250   share of organic N inputs originating from non-animal manure sources (e.g. municipal and slaughterhouse wastes). Then (4),

manure remaining in conventional animal production systems are distributed to crop areas used for feed in the same region, and finally (4), any remaining manure in a region is distributed to conventional areas within the same region.

After accounting for TAN and long-term N release from applied manure, residual plant available N requirements are used to allocate other organic fertilisers (such as biogas digestate, see section 2.9). This follows a similar procedure as manure by first

255   (1) distributing organic fertilisers generated in each region to organic crops within the same region. Second (2), the remaining organic fertilisers are distributed nationally to organic areas. And finally, remaining organic fertilisers are distributed to conventional areas regionally (3) and nationally (4).

P and K in manure and other organic fertilisers are distributed proportionally to the N distribution (i.e. if 5% of N in cattle manure in a region is distributed to a certain crop 5% of P and K in cattle manure is also assumed to be distributed to that

260   crop).

Finally, remaining N, P and K requirements are met through mineral fertiliser inputs. Thus, the model endogenously calculates mineral fertiliser use based on crop requirements, residual N from crops in rotation, and availability of manure and other organic fertilisers.

2.6.3   Lime application

265   Requirements for lime are calculated based on the acidifying or liming effects of N, P and K fertilisers and manure application as well as the excess alkali of harvested crop products and residues removed from the fields (Sluijsmans 1966; Persson 2003). For each item, parameters are supplied for their liming (or acidifying) effect in terms of calcium oxide (CaO) equivalents per kg N, P or K in fertilisers or manure, or per kg dry matter for crop products and residues. In order to calculate the total use of different liming agents, parameters are also supplied for the shares of different liming agents used and their respective

270   neutralising value relative to CaO.

2.6.4   Emissions to the environment from fertilisers, manure and lime

NH_3-N losses from fertilizer and manure applications are calculated using emission factors per kg of N (or per kg of TAN for manure) as outlined by (Swedish Environmental Protection Agency 2023b). These emission factors are provided as parameters and vary by fertiliser type, manure management system, and animal type. N_2O-N emissions are estimated according to the

275   IPCC (2019) methodology, where N additions from fertilisers, manure, other organic fertilisers, and crop residues (both above and below ground) are multiplied by an emission factor representing the proportion of N emitted as N_2O.

The calculation of N quantities in applied fertilisers and manure is detailed in section 2.6.2. N content in crop residues, both above and below ground, is estimated based on crop yield, residue production per harvested crop, and the N content of residues, all supplied as parameters. For crops that or not harvested such as fallow and green manures, a potential yield is specified and

280   used to quantify generated crop residues. For above-ground residues, the amount removed is estimated based on the demand for crop residues as bedding material (calculated in the *AnimalHerd* modules) and for other uses (specified in the *DemandAndConversions* module).

N$_2$O emissions from cultivated organic soils are calculated by applying emission factors per hectare to the share of cropland on organic soils, as specified in the *Regions* module.

285   In the current model version, leaching is only considered for N, calculated as a specified proportion of N in organic and mineral fertilisers and crop residues that is assumed to leach according to the IPCC (2019) Tier 1 approach. Indirect N$_2$O emissions from deposition and leaching are not calculated directly in CIBUSmod outputs but are addressed in subsequent impact assessment stages.

   Lastly, CO$_2$ emissions from liming are estimated based on quantities of applied lime (see section 2.6.3) and emission factors

290   per liming agent in accordance with the IPCC (2019) Tier 1 methodology.

2.7   Energy use in agriculture

Agricultural energy use is handled with the *MachineryAndEnergyMgmt* module, which calculates energy use for field machinery, grain dryers, greenhouses and animal stables. This module also calculates emissions from fuel combustion. For each energy-using activity, the model allows specifying the share of energy from different sources, such as diesel or biodiesel

295   for field machinery, or fuel oil, biofuels or electricity for animal stable heating.

   Energy use for different field operations is calculated either from power calculations, where energy requirements for tractor and implements are calculated separately based on equations in ASABE (2006) and Robert Bosch GmbH (2014), or from fixed factors for energy requirements per hectare and/or harvest mass for different field operations. The former method is used for soil texture dependent operations, such as ploughing, harrowing and cultivation, thus accounting for regional differences in

300   soil texture when calculating energy requirements. In both cases the useful energy at the implement is calculated first, after which an efficiency factor that accounts for losses in the power take-off, drivetrain and engine is applied to calculate the total gross energy required in the form of fuel. This allows to parametrise alternative drivetrains such as electric or hydrogen fuel cells. After calculating the total energy use for different field operations, these are multiplied by the number of times a specific field operation is performed for a given crop and production system, which allow for e.g. distinguishing between organic and

305   conventional agriculture in terms of machinery operations, or modelling effects on energy use from implementing low/no-till systems.

   To estimate the energy used for manure application, the total cropland area that receives manure is calculated. Then, specific factors for useful energy required per hectare are applied. The total cropland area receiving manure is calculated in the *PlantNutrientMgmt* module based on a user-specified minimum share of N that must come from manure where applied. For

310   example, if a crop requires 100 tonnes of N in total, with 50 tonnes provided by manure, and the minimum share of N from manure is set at 75%, then 67% of the crop's total area will be assumed to receive manure (50 / (100 × 0.75) = 0.67). This approach allows energy use for manure application to follow directly from the amount of manure generated in different scenarios.

   Energy use in grain dryers is calculated based on the useful energy required per kg water removed, dryer efficiency and water

315   content at harvest and after drying for different crops, as well as a factor for auxiliary energy requirements. For greenhouses,

energy requirements are calculated based on user-specified energy use per square meter for different crops. Energy use in animal stables is calculated by specifying energy use per head, per inserted head or per unit of production or a combination of those. This allows the incorporation of varying datasets where the energy use is expressed in different terms. It is also possible to disaggregate stable energy use by specifying sub activities such as stable heating, stable machinery, or stable lighting which can have different mixes of energy sources.

2.8 Supply chain emissions from energy carriers, fertilisers and other inputs

To account for environmental impacts incurred throughout the supply chains of inputs used, the *InputsMgmt* module can connect each input to an Ecoinvent process and automatically retrieve inventory data. The connection to Ecoinvent is handled with the *ecoinvent-interface* Python package (https://pypi.org/project/ecoinvent-interface/) and requires an Ecoinvent account with access to the database. It is also possible to manually specify emissions from inputs when a suitable Ecoinvent process is lacking. Currently the inputs accounted for in the model are all the energy inputs (e.g. electricity and diesel), N, P, and K fertilisers and lime.

2.9 Waste management and circularity

The *WasteAndCircularity* module manages the treatment of generated waste and losses. This module accounts for food waste and losses occurring at processing, retail, and household stages, culled animals, surplus by-products (i.e., instances where by-product generation exceeds demand for food and feed), and animal manure sent to centralised treatment. For surplus by-products, users can specify the proportion directed to waste treatment versus export in the *ByProductMgmt* module. The *WasteAndCircularity* module can also handle the treatment of non-waste biomass for bioenergy production, such as through anaerobic digestion.

For each waste fraction and non-waste biomass type, the proportion processed by different waste treatment methods is specified in the input parameters. So is the N, P, K and VS content of each waste fraction.

Calculations for different waste treatment methods are managed by dedicated functions. Currently, functions for anaerobic digestion, incineration, and landfill are included. Each function calculates (as applicable) the generated and used energy , the N, P, K, and C losses (e.g. in the form of NH_3, N_2O and CH_4) to the environment, and the N, P, K and C content in the generated organic fertiliser available for application to agricultural land. The *WasteAndCircularity* module is also designed to allow easy, programmatic addition of custom functions for new waste treatment methods without altering the main model code.

3 Application to a case study - Sweden

This section provides an example application of CIBUSmod on a case study, focusing on the Swedish agri-food system. In section 3.1, the baseline data collection and validation is described, and in section 3.2 the results from modelling two future scenarios using CIBUSmod, is presented.

3.1 Input data and baseline validation

Input data for the baseline were collected for the years 2016-2020. When available, a 5-year average for 2016-2020 was used. When data was not available for the entire country or time period, estimates from single case-studies or older data was used. Data were compiled from national statistics, statistics from industry organisations, published reports and peer reviewed
350 publications. The following sections briefly describes the main data sources used in the different modules of CIBUSmod and provides validation of key output variables against previously published estimates and national statistics. The baseline dataset for Sweden, with references to data-sources, is provided open-source together with the model code in the model's GitHub repository.

3.1.1 Demand for agricultural production and process conversion factors

355 Swedish food consumption of approx. 70 food items (for the year 2020) was estimated from national statistics (The Swedish Board of Agriculture 2024) and FAOSTAT food balance sheets (FAO 2024). Import shares were taken from Schwarzmueller and Kastner (2022) for most products, and national statistics (The Swedish Board of Agriculture 2024) for dairy products. Factors for food waste at processing, retail, and household stages, were based on estimates from Gustavsson *et al.* (2011) and conversion factors for translating food consumption (as eaten) into demand for raw agricultural commodities and associated
360 by-product generation rates, were sourced mainly from FAO (2000). Organic proportions of the domestically produced foods were taken from national statistics (The Swedish Board of Agriculture 2024).

3.1.2 Crop production

The model was parametrised with around 60 crops, covering major cereals such as winter wheat and spring barley, forage crops like ley for silage or grazing, four classes of semi-natural grasslands, grain legumes, rapeseed, as well as various
365 horticultural crops, greenhouse cultivated crops, and fruit trees. The areal extent of different crops used in the optimisation goal function (see section 4) was based on data from the Land Parcel Identification System (LPIS), provided by the Swedish Board of Agriculture, aggregated over "harvest regions". These regions subdivide Sweden into 106 agronomically uniform areas which represent the smallest spatial scale on which national agricultural statistics on e.g. yields are presented. This is also the geographic scale used in the model for the case study. The LPIS data was further treated to disaggregate horticultural
370 crops (presented as one category in LPIS data) to individual crop types and to separate conventional and organic areas. This was based on publicly available statistics on larger regional level or national level from The Swedish Board of Agriculture (2024).

Crop yields were estimated from the Swedish Board of Agriculture's statistics on "harvest region" level, where available. For many crops and regions, however, yield data is unavailable at harvest region level. In these cases, yields were extrapolated
375 based on data from larger spatial scales (such as county, or national levels), along with a "reference crop" with good data coverage (usually spring barley). This method generates yield estimates for every crop across all regions. For crops with limited

data, the extrapolated yields are highly uncertain. However, because the model allocates crops based on their current distribution, regions with more available yield data typically have much larger cultivated areas, which limits the impacts of this uncertainty.
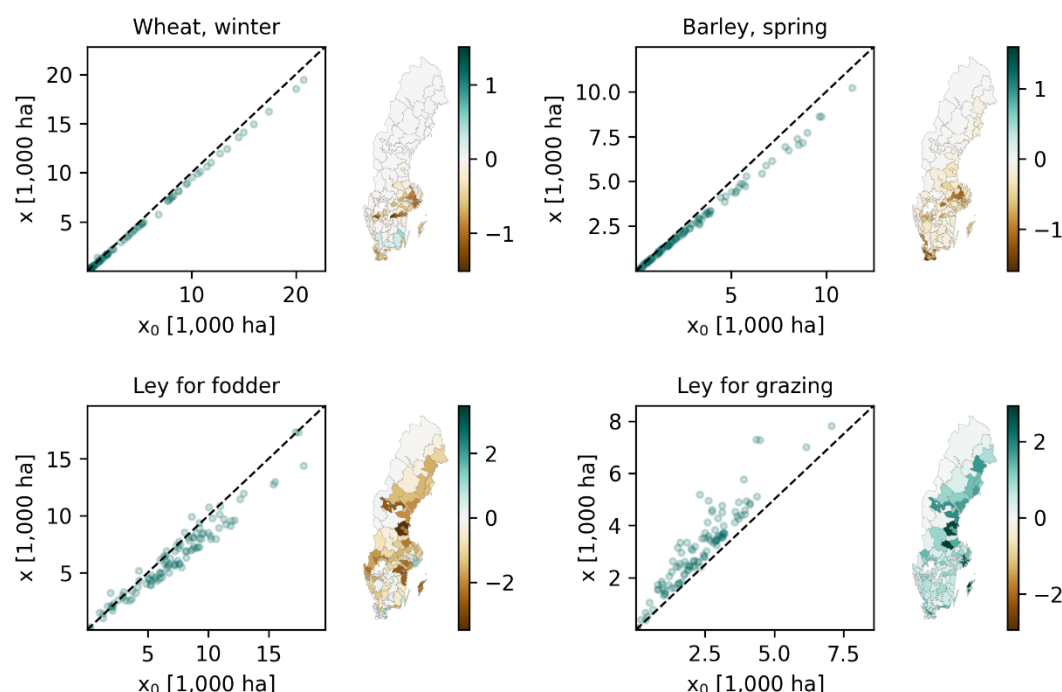

Figure 3. Regional distribution of crop areas in CIBUSmod (x) compared to crop areas estimated from national statistics and LPIS data (x_0). The dashed lines shows the 1:1 lines. The maps show $x - x_0$ per region.

Figure 3 shows the modelled distribution of four major crops compared to the current distribution based on LPIS data. For the two cereal crops, the model closely matches the current distribution, though with a slight underestimation in total demand. This leads to an underestimation of areas in the key cereal-growing districts in central and southern Sweden. The distribution of leys shows greater discrepancies. These are due to constraints that require at least 95% of forage crops to be produced in the same region as the animals consuming them. It is an indication that forage crops and/or animals are likely moved across regional borders to a larger extent than allowed under the set constraints. Additionally, the model overestimates the area of grazed leys and underestimates leys for fodder production, particularly in northern Sweden. This discrepancy arises from the shorter grazing season in northern Sweden, which reduces the share of grazing in local feed rations. Since feed rations are currently implemented as national averages in the input data, regional differences in grazing periods are not captured.

3.1.3 Livestock production

The number of animals in each region was estimated based on national statistics, providing animal counts per municipality in June (The Swedish Board of Agriculture 2024). These counts were then distributed over to the "harvest regions" using area

395 overlaps to create the initial state used in the optimisation goal function (see section 4).

Livestock productivity parameters, including fertility, slaughter ages, slaughter weights, and mortality were sourced from national statistics, published papers, and reports. For cattle, data primarily came from Växa cattle statistics (www.vxa.se/statistik), Einarsson *et al.* (2022) and Ahlgren *et al.* (2024). For sheep, Ahlgren *et al.* (2024) was the main source. For pigs, data were taken from Gård & Djurhälsan's WinPig statistics (https://www.gardochdjurhalsan.se/winpig/), Landquist

400 *et al.* (2020), and Zira *et al.* (2021). For broiler chickens, data were mainly sourced from Edman *et al.* (2022) and for laying hens data were sourced from Sonesson *et al.* (2008) and Carlsson *et al.* (2009). Animal feed rations were also gathered from the above mentioned sources, but for cattle and horses the concentrate component of animal diets was adjusted based on national feed industry statistics.

Overall, the estimated number of animals and their regional distribution closely match the statistics on animal numbers (Figure

405 4). For cattle, there is a slight underestimation in northern Sweden, offset by an overestimation in central and southern areas, likely due to feed rations not reflecting regional variations, as previously discussed.

For horses, there is a significant underestimation in the region with the highest current horse population. One of the models constraints is a requirement that at least 95% of forage demand in each region is met locally. However, in this densely populated region, horse keeping likely relies more on forage sourced from neighbouring areas, which may explain why the model does

410 not align with the observed horse numbers.

For pigs and poultry, some regions show larger deviations. However, these discrepancies are relatively small when considering total population sizes.
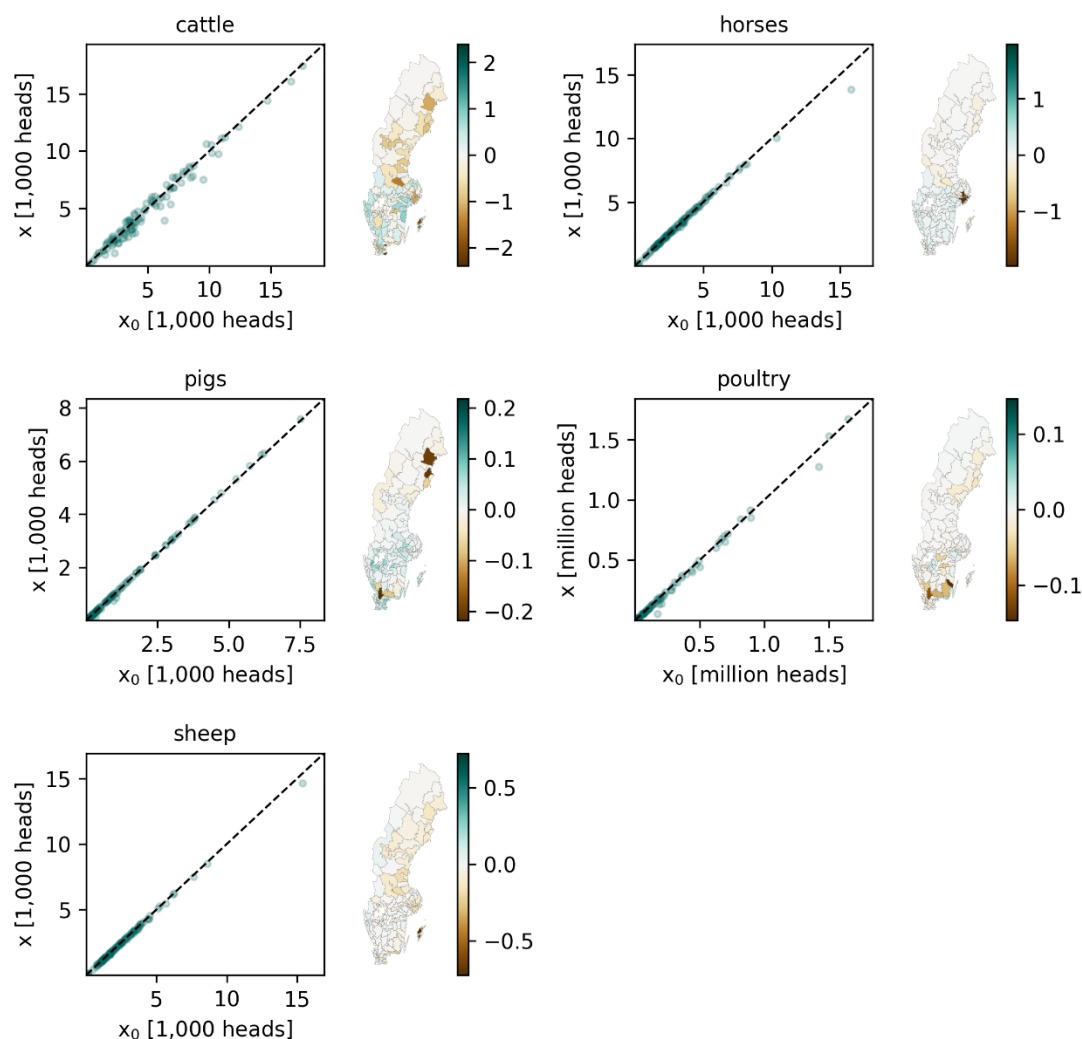
Figure 4. Regional distribution of animals in CIBUSmod (x) compared to animal numbers estimated from national statistics (x_0). The dashed lines shows the 1:1 lines. The maps show $x - x_0$ per region. Animal numbers are expressed in terms of the number of the defining animal category per species (cows for cattle, ewes for sheep, total horses, sows + gilts for pigs and broilers or laying hens for poultry).

In Sweden, statistics on animal feeding practices are not routinely collected, which makes it difficult to validate assumptions about feed rations. The feed industry do however report data on the raw materials used in compound feeds. Many crop products

and some by-products used in animal feed bypass the feed industry and are thus not represented in these statistics. For by-products that are primarily supplied through compound feeds, some validation was possible using national statistics, as shown in Figure 6. This comparison generally shows reasonable alignment, although the assumed feed rations here lead to an overestimation of soybean meal use and an underestimation of rapeseed meal use. This discrepancy is likely due to recent efforts in Sweden to reduce soybean meal in animal feed, given its association with deforestation in South America—a shift that was not reflected in the data used to estimate feed rations.
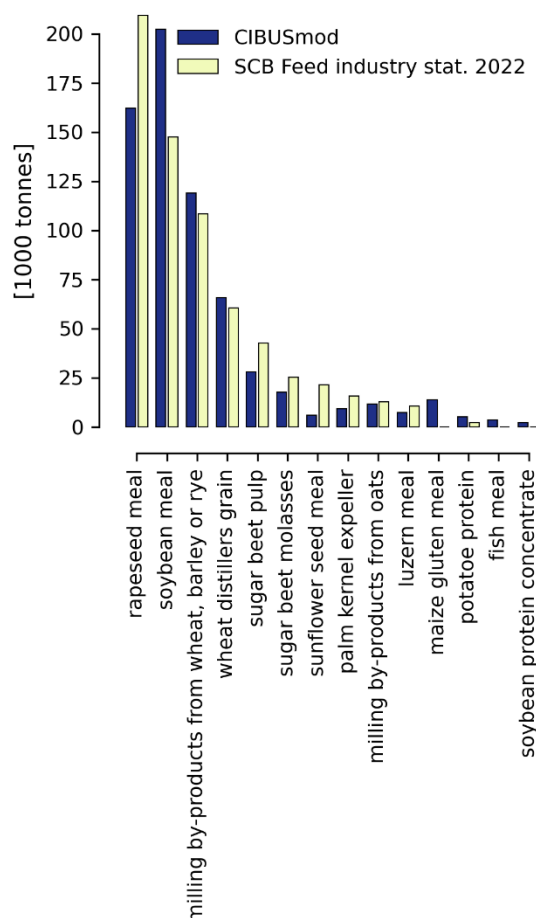
Figure 5. Use of by-products in animal feed estimated in CIBUSmod compared to national feed industry statistics for year 2022.

3.1.4 Fertiliser and manure

Parameters used to estimate crop N, P and K requirements were sourced mainly from national fertiliser recommendations from the Swedish Board of Agriculture (2023), using region- and soil class-specific recommendations when available. For crops not covered by national recommendations (e.g. vegetables, barriers and fruit), recommendations from fertiliser manufacturers or values from previous studies were used.

Data used to estimate manure N, P and K excretion for cattle and pigs under the mass-balance approach was based on Dutch data (Statistics Netherlands 2012). For other livestock categories excretion rates per head were sourced from (Swedish Environmental Protection Agency 2023a) for N and from Statistics Netherlands (2012) for P and K. Emission factors used in estimating N losses in stables and manure storage were sourced from the (Swedish Environmental Protection Agency 2023b) and the European Environment Agency (2023).

The total N excretion in manure is estimated at 143,000 tonnes in CIBUSmod, with 17% lost during storage and in stables (Table 3). This total excretion is 7% higher than the estimates by Einarsson *et al.* (2022), resulting in proportionally larger losses estimated in CIBUSmod. The discrepancy is due to differences in methodology: Einarsson *et al.* (2022) estimated manure excretion using fixed factors per animal, whereas a mass-balance approach is used in CIBUSmod for cattle and pigs. However, estimates from CIBUSmod are well in line with national statistics on to total manure application on cropland for both N and P (Figure 3). Considering the complexity and uncertainties, the mass-balance approach for calculating N, P, and K excretion yields estimates within an acceptable range of other estimates. Unlike fixed excretion rates per animal, this approach offers the advantage of internally calculating excretion rates based on animal productivity, the feed requirements and its composition.

Table 3. Estimated nitrogen (N) in excreted manure and losses in stables and during manure storage in CIBUSmod compared to estimates reported in Einarsson et al. (2022). Values are given in 1000 tonnes N.

	CIBUSmod	Einarsson *et al.* (2022)	Difference
Excretion	**143**	**134**	**+7%**
Stable/storage losses	**24.8**	**21.7**	**+14%**
NH_3-N	19.4	17.2	
N_2O-N	0.56	0.51	
NO_X-N	0.15	0.13	
N_2	4.68	3.92	
Share of excreted lost	*17%*	*16%*	
Applied (incl. grazing)	**118**	**112**	**+5%**
Application/soil losses	***18.7***	***17.2***	**+9%**
NH_3-N	17.3	15.8	
N_2O-N	1.44	1.41	

Total mineral N fertiliser application on cropland in CIBUSmod is estimated at 145,000 tonnes, which is 15% lower than the figure reported in national statistics (Figure 3). This discrepancy is due to an underestimation of total crop areas in the model compared to national statistics data. When crop areas from national statistics were used directly in the model, estimated mineral N fertiliser application was 1% higher than reported in national statistics.
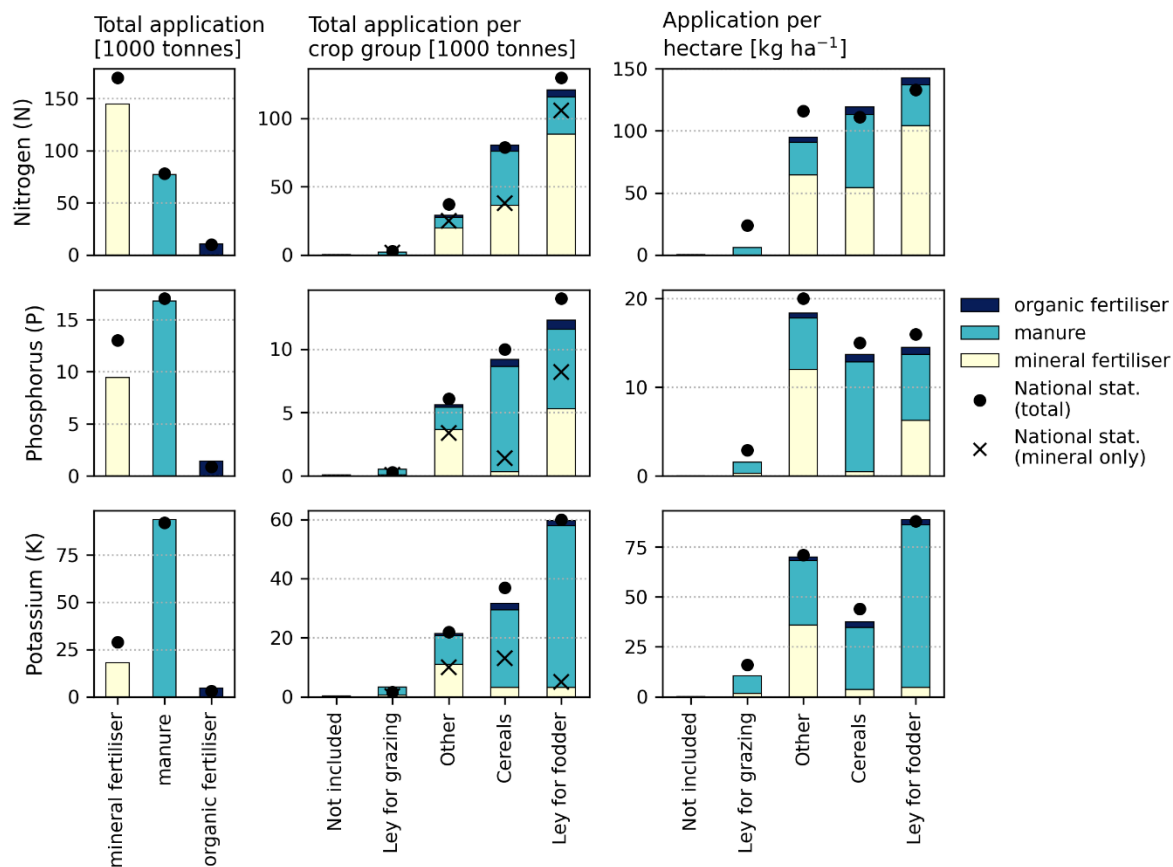
Figure 6. Nitrogen (N), phosphorus (P) and potassium (K) application on cropland in CBUSmod compared to national fertiliser statistics (average 2016-2020). Bars show results from CIBUSmod and points and crosses show total and mineral fertiliser application according to national statistics, respectively.

The regional distribution of N application in mineral fertilisers and manure estimated in CIBUSmod follows the general patterns observed in national statistics (Figure 7). But, application rates of mineral fertiliser in the forest-dominated south-central and northern parts of Sweden are lower in CIBUSmod compared to national statistics.
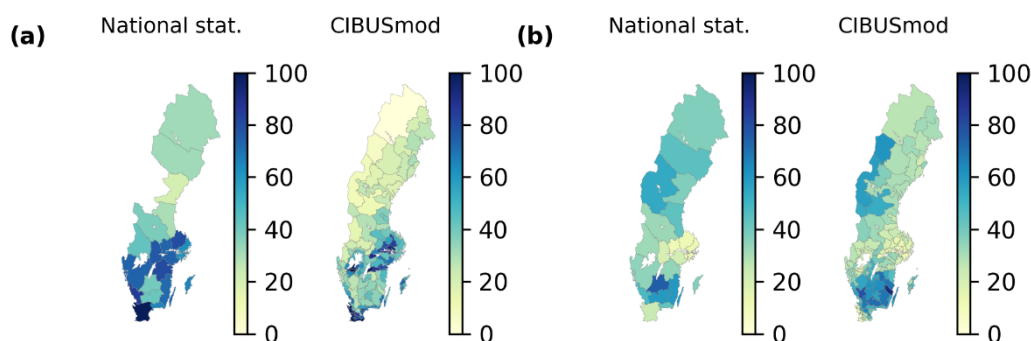
Figure 7. Geographic distribution of mineral fertiliser (a) and manure (b) nitrogen application on croplands according to national fertiliser statistics and in CIBUSmod expressed as kg N ha⁻¹.

465 **3.1.5   Energy use**

Data for the parameters used in estimating energy use for field machinery, grain dryers, animal stables and greenhouses were compiled from a number of sources, comprising mainly of Swedish technical reports, including an inventory of energy use in Swedish agriculture commissioned by the Swedish Board of Agriculture and summarised in Baky *et al.* (2010). For the main tractor implements, soil-type-specific parameters were sourced from ASABE (2006). Figure 8 shows that estimated energy

470 use in CIBUSmod aligns well with those previously presented by Baky *et al.* (2010), albeit with some exceptions, notably for pig and broiler stables where substantially lower energy use was estimated using CIBUSmod.
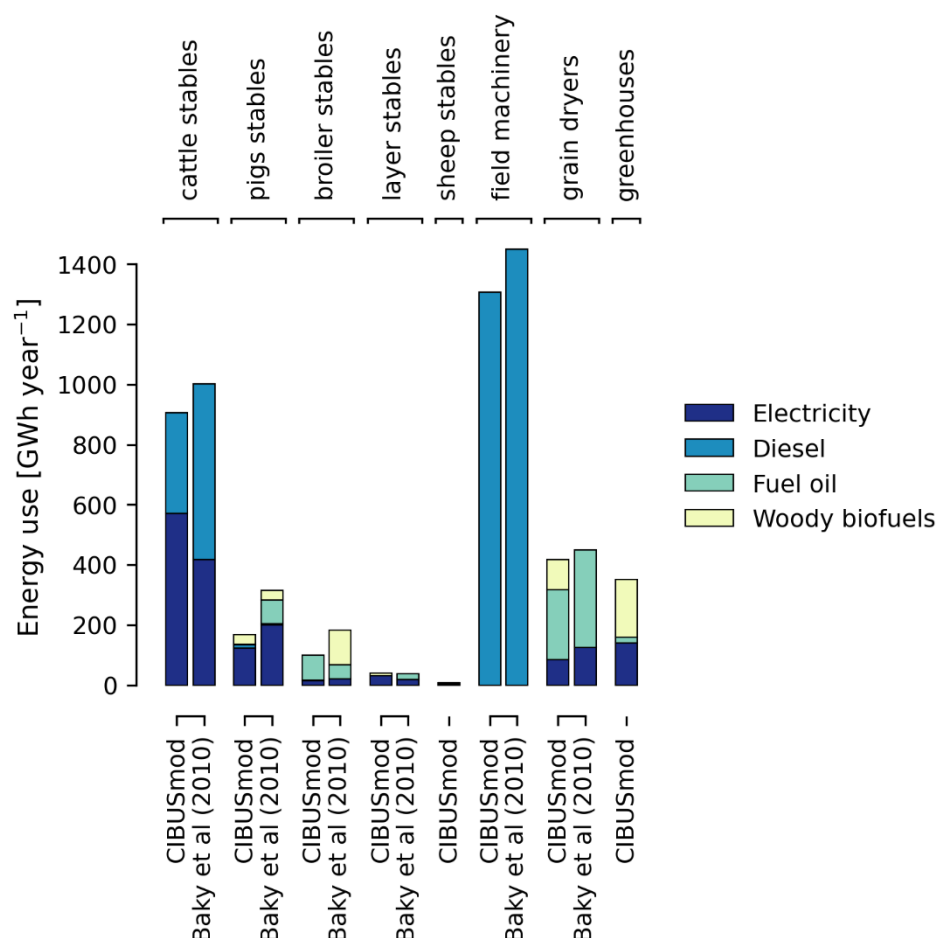
Figure 8. Energy use in stables, field machinery, grain dryers and greenhouses subdivided by energy source estimated in CIBUSmod compared to estimates by Baky et al. (2010).

475 **3.1.6 Greenhouse gas emissions**

Figure 9 compares methane and nitrous oxide emissions from Sweden's national greenhouse gas inventory with those estimated by CIBUSmod, which shows that emissions estimated in CIBUSmod largely are in agreement with values in the national inventory. For methane, the results show good agreement for enteric fermentation (Figure 9, 3.A). However, for manure management (Figure 9, 3.B(a)), CIBUSmod estimates significantly higher emissions for horses and poultry. The

480 national inventory uses fixed emission factors per head from IPCC (2006) for these livestock categories, while CIBUSmod bases emissions on volatile solids (VS) excretion, which in turn is derived from gross and digestible energy in feed rations (see section 2.5) for all livestock. Default VS excretion for poultry are given as 0.010 kg VS per animal and day for broilers and 0.020 kg VS per animal and day for laying hens with a margin of error of +/- 50% in IPCC (2006). In contrast, the estimates from CIBUSmod, based on feed consumption, are twice as high for broilers (0.020 kg VS) while for laying hens estimates

485 align more (0.022-0.024 kg VS). Moreover, the methane emission factors used in the national inventory are based on only dry manure management systems for laying hens. In the case study it is assumed that 8% of laying hens have a liquid manure management system, in accordance with the Swedish Environmental Protection Agency (2023b), which has more than an order of magnitude higher MCF factor than dry systems (IPCC 2019). Together, these methodological differences explain the large discrepancies in emission estimates.

490 For nitrous oxide emissions from manure management (Figure 9, 3.B(b)), the results are more consistent between the two sources, but CIBUSmod estimates higher emissions, particularly for cattle and pigs. The mass balance approach used in CIBUSmod to estimate N excretion (see section 2.5.1) result in higher excretion rates than the figures used in the national inventory, which explains the difference.
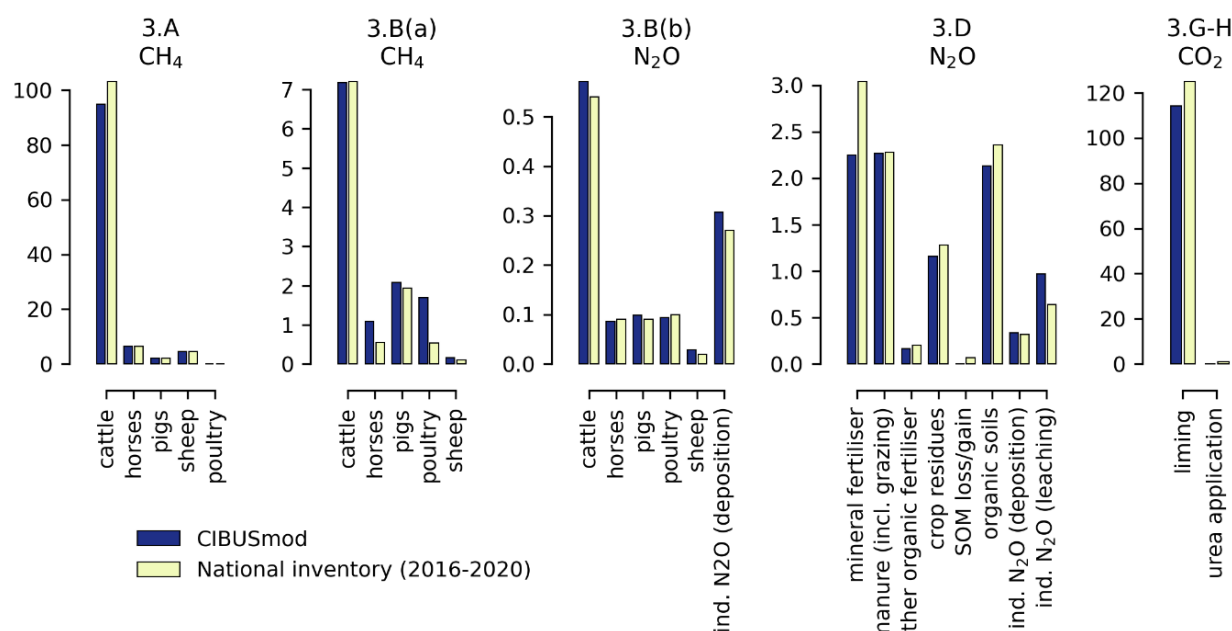

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Figure 9. Agriculture sector emissions in 1000 tonnes of carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O) as reported in Sweden's National Inventory Report (NIR) to the United Nations Framework Convention on Climate Change (average for 2016-2020) compared to corresponding emissions estimated in CIBUSmod. The labels correspond to the common reporting format (CRF) table numbers: 3.A = Enteric Fermentation, 3.B(a) = CH_4 Emissions from Manure Management, 3.B(b) = N_2O Emissions from
500 **Manure Management, 3.D = Direct and indirect N_2O emissions from agricultural soils, 3.G-H = CO_2 emissions from liming, urea application and other carbon-containing fertilizers.**

Regarding nitrous oxide emissions from agricultural soils (Figure 9, 3.D), CIBUSmod estimates lower emissions from mineral fertiliser application due to the underestimation of fertiliser use, as discussed earlier, while for manure estimates agree with the national inventory. Moreover, emissions from crop residues are estimated slightly lower in CIBUSmod compared to the

505 national greenhouse gas inventory. This is partly explained by a larger share of crop residues being removed in the CIBUSmod. In CIBUSmod the fraction of crop residues removed is endogenously calculated based on demand for bedding material in

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stables. This may indicate that parameters used for estimating the use of bedding materials overestimate total demand or that use of straw is underestimated in the national inventory. CIBUSmod also estimates much larger indirect nitrous oxide emissions from leaching compared to the national inventory. This is because leaching in CIBUSmod is modelled as a fixed

510   share of applied N, according to IPCC (2019) Tier 1 methodology, which likely overestimates leaching. For the national inventory, a more sophisticated process-based model is used to estimate leaching.

For nitrous oxide emissions from managed organic soils slightly lower emissions were estimated in CIBUSmod than reported in the national inventory. This is a net effect of the total area of cropland on organic soils being lower in CIBUSmod than in the national inventory (mainly due to a lower total cropland use) and that emissions from semi-natural grasslands on organic

515   soils are included in CIBUSmod, which are reported under forestry in the national inventory. Data on the share of cropland and semi-natural grasslands on peat soils from Lindahl and Lundblad (2021) was used to estimate the area of organic soils.

Carbon dioxide emissions associated with liming are slightly lower in CIBUSmod than in the national inventory (Figure 9, 3.G-H) due CIBUSmod estimating a lower use of lime. Emissions from urea are not estimated in CIBUSmod, but these emissions are negligible in Sweden.

520   **3.2   Scenario example – Re-assessing scenarios for organic farming in Sweden**

In this section, an example of model runs comparing two scenarios is presented to illustrate the model's behaviour and its outputs. Both scenarios were modelled from 2020 to 2050, using 2020 as the baseline year. The scenarios were based on the "Base20" and "Sust50" scenarios for Sweden, originally developed by Basnet *et al.* (2023). In Basnet *et al.* (2023) these scenarios were modelled using the FABLE Calculator (Mosnier *et al.* 2020).

525   The Base20 scenario represents a business-as-usual pathway. It incorporates crop and livestock productivity improvements, as well as population growth. In contrast, Sust50 envisions a shift to organic farming covering approximately 50% of Swedish cropland by the year 2050 (implemented in CIBUSmod by increasing organic food consumption). In this scenario diets change to include fewer animal-source foods and more vegetables and fruits, household food waste is reduced by 50%, and productivity improvements are stronger than in Base20. Import shares are held constant for all foods in both Base20 and

530   Sust50, but the Sust50 scenario includes increased organic cereal exports. Further details on scenario definitions can be found in Basnet *et al.* (2023).

In addition to the definitions provided by Basnet *et al.* (2023), several adjustments were made to the Sust50 scenario to ensure adequate nutrient supply in organic cropping systems. Specifically, the area dedicated to green manure in organic systems was increased by enforcing at least 10% of organic cropland devoted to green manures. The maximum share of cereals in organic

535   crop rotations was also constrained (8% and 15% for winter and spring cereals, respectively) to limit regional nutrient requirements. The proportion of food waste directed to anaerobic digestion was increased, from 40% in 2020 to 80% for household food waste and 100% for processing and retail food waste. Grass-legume ley cultivation was also introduced as feedstock for anaerobic digestion in order to increase nutrient supply in the form of digestate as an organic fertiliser. In both scenarios, total cropland increase was constrained not to increase by more than 20% from baseline levels in any region.

3.2.1 Scenario example results

Consistent with Basnet *et al.* (2023), the cropland areas from CIBUSmod remain stable in the Base20 scenario, as productivity improvements meet the rising demand driven by population growth (Figure 10). However, while Basnet *et al.* (2023) report a reduction in cropland use under the Sust50 scenario, the results from CIBUSmod indicate unchanged cropland use in 2050 compared to 2020. A major reason for this discrepancy is the assumed increase in green manure in CIBUSmod, where this area increases from less than 1% of organic cropland in 2020 to 10% in 2050 (Figure 12b). This contributes to adequate N supply for organic crop production.
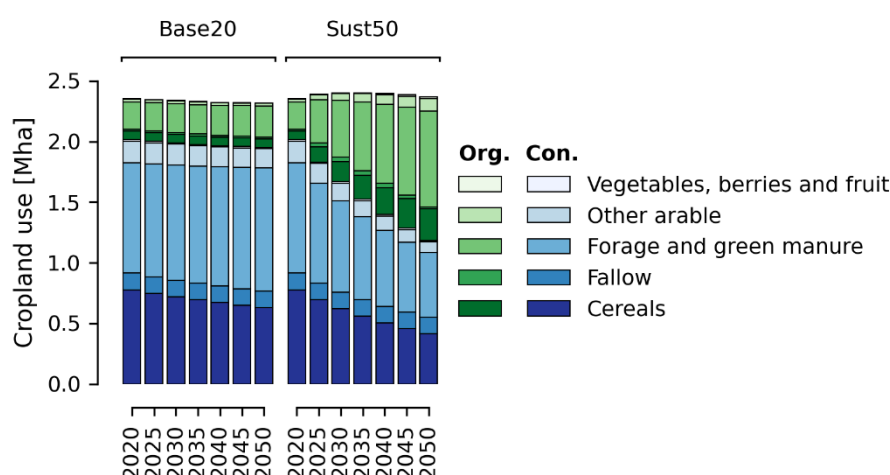

Figure 10. Development of cropland use for the two scenarios. Blue and green shades show conventional and organic areas respectively.

In the base year, 56 kg of N per hectare was applied to organic cropland (Figure 11a) through animal manure and other organic fertilisers (i.e. biogas digestate from anaerobic treatment of waste and manure). Approximately 24% of N input to organic farming originated from conventional animal manure. This flow of nutrients from conventional agriculture underscores the dependence of current organic production systems on conventional nutrient sources, as highlighted by e.g. Nowak *et al.* (2013) and Vergely *et al.* (2024). Under the Sust50 scenario, N application to organic cropland increased to 62 kg N ha^{-1}, despite the increase in green manures, due to an increased share of organic cropland devoted to cereals. In CIBUSmod, N fixation from green manure and other leguminous crops is not directly visible in outputs. It is instead accounted for indirectly through crop-specific parameters for residual N which becomes available to subsequent crops in the rotation. This effectively reduces N requirements. The increased N fixation in green manures, along with increased digestate supply from anaerobic digestion of food waste and ley biomass (Figure 12a) reduced the reliance on conventional animal manure for organic production to 14% of total N inputs in the Sust50 scenario (Figure 11b).
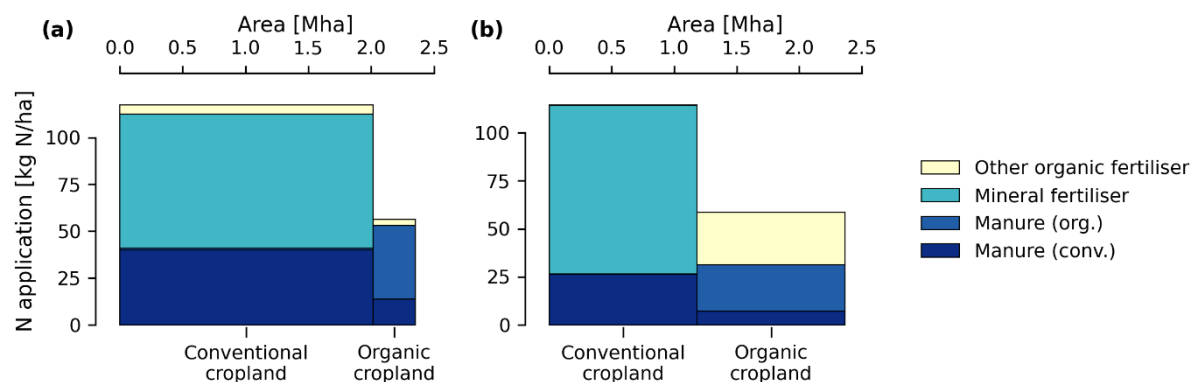
Figure 11. Distribution of nitrogen (N) in mineral fertilisers, manure and other organic fertilisers (i.e. biogas digestate) to conventional and organic cropland in the base year 2020 (a) and in 2050 for the Sust50 scenario (b). The x-axis shows the total cropland area and the y-axis N application per hectare. The area of each box is thus proportional to total N application.

565   In the Base20 scenario, animal manure N application increased, while reduced animal-source food consumption in the Sust50 scenario led to reduced livestock populations and manure supply (Figure 12d). In the Base20 scenario, mineral N fertiliser use reduced slightly while the Sust50 scenario led to a substantial reduction in fertiliser use, from around 145 kt N in the base year to 106 kt N in 2050 (Figure 12c).
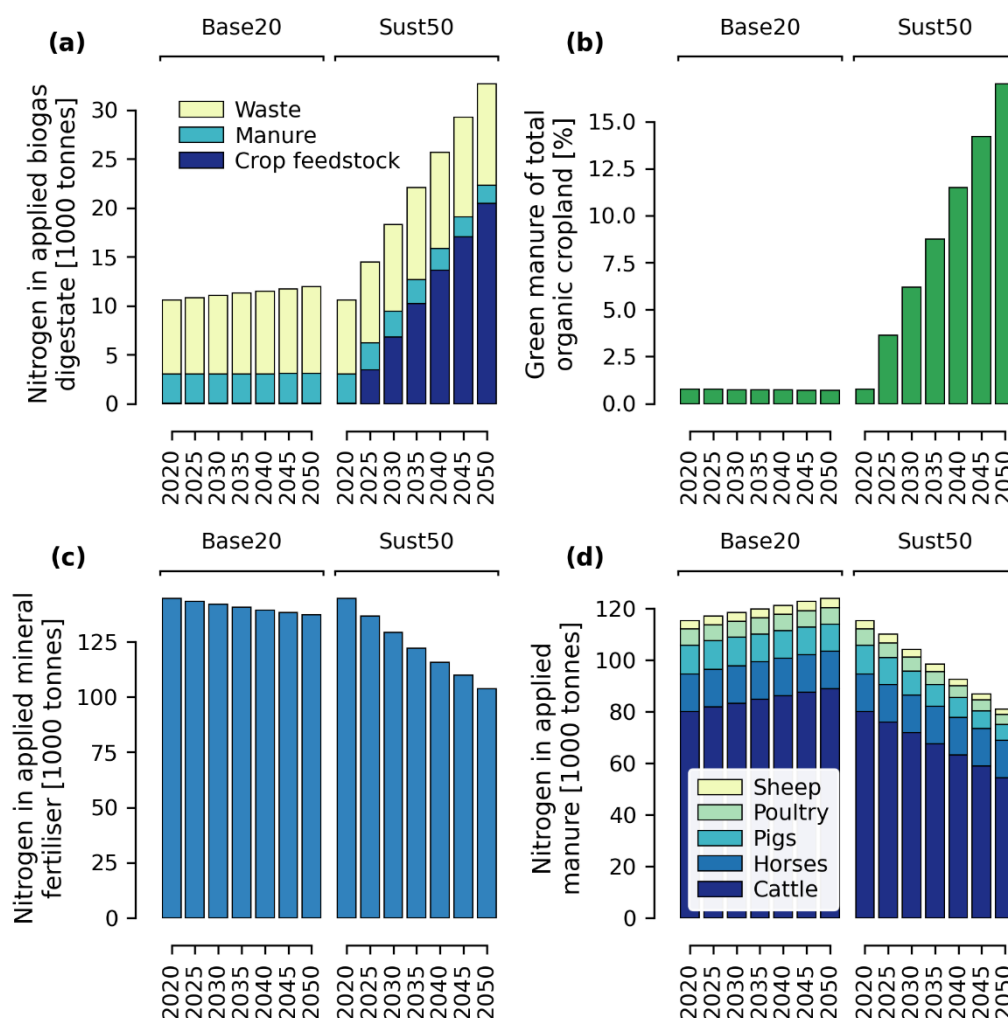
Figure 12. Development of key variables for nitrogen supply for the two scenarios. a) Nitrogen in applied digestate per feedstock type, b) share of total organic cropland devoted to green manure, c) applied mineral fertilisers and d) applied animal manure per livestock species.

In the Base20 scenario, GHG emissions from the agricultural sector (including energy use and input supply chain emissions) increased, whereas in the Sust50 scenario, emissions of CO_2, CH_4, and N_2O were reduced by 7%, 24% and 15%, respectively, by 2050 (Figure 13). The total climate impacts in CO_2-equivalent terms were reduced by 15%. This was largely due to decreased livestock numbers and mineral N fertiliser use. In the original scenario assessment by Basnet *et al.* (2023), production emissions in CO_2-equivalent terms were projected to decrease by approximately 38% from 2010 to 2050 under the Sust50 scenario. Additionally, a net carbon sequestration opportunity due to reduced cropland requirements was identified. In contrast, results from CIBUSmod indicates unchanged cropland use, and thus no opportunities for increasing carbon

580 sequestration through afforestation. Consequently, the results from CIBUSmod suggests that while the Sust50 scenario has substantial emissions reduction potential, it is lower than estimated in Basnet *et al.* (2023).
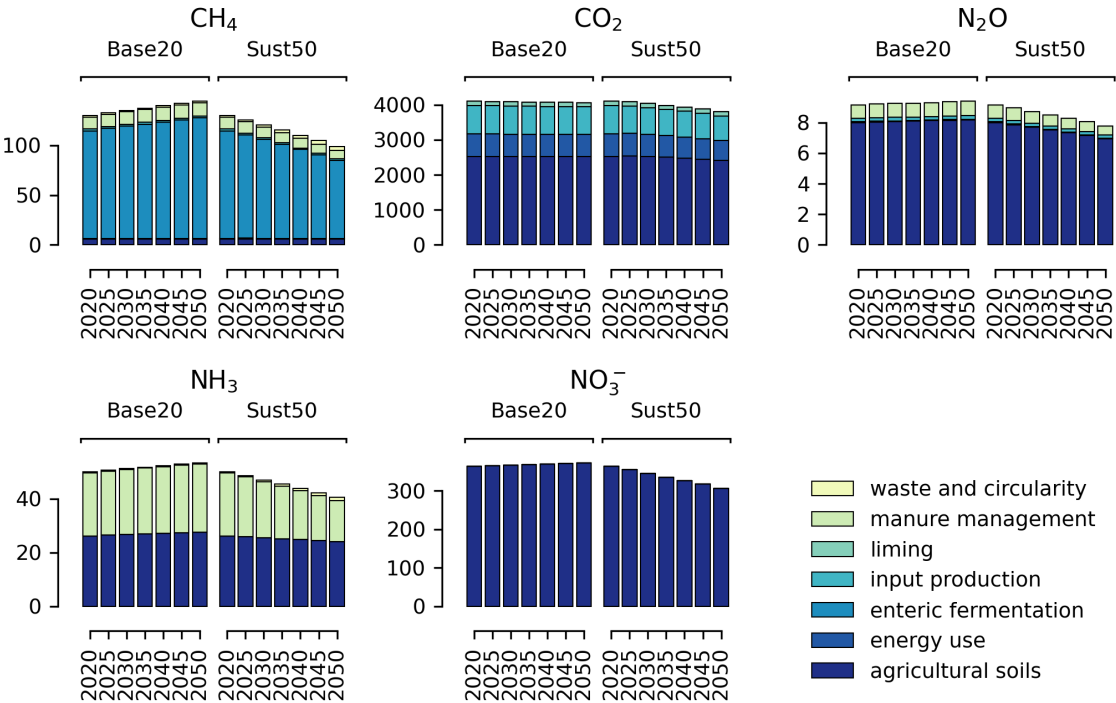

Figure 13. Development of yearly emissions [1000 tonnes] of methane (CH₄), carbon dioxide (CO₂), nitrous oxide (N₂O), ammonia (NH₃) and leaching of nitrate (NO₃⁻) under the Base20 and Sust50 scenarios.

585 The share of cropland under organic farming ranged from 17–68 % across regions. It followed approximately the initial distribution of organic cropland areas (Figure 14a), which is expected as deviations from the initial state is minimised in the model. The assessment of regional N budgets showed that biogas digestate would need to be moved from regions with surplus to those with a deficit to meet local crop nutrient requirements. In the Sust50 scenario, it was assumed that biogas digestate would be prioritised for organic areas to reduce reliance on conventional animal manure in organic farming. This would pose

590 major logistical challenges. Increasing the use of conventional animal manure on organic cropland, or directing animal farming and ley production for anaerobic digestion to more productive regions with high crop N requirements, could potentially reduce the need for transport of N between regions. This was however not investigated further in this study.
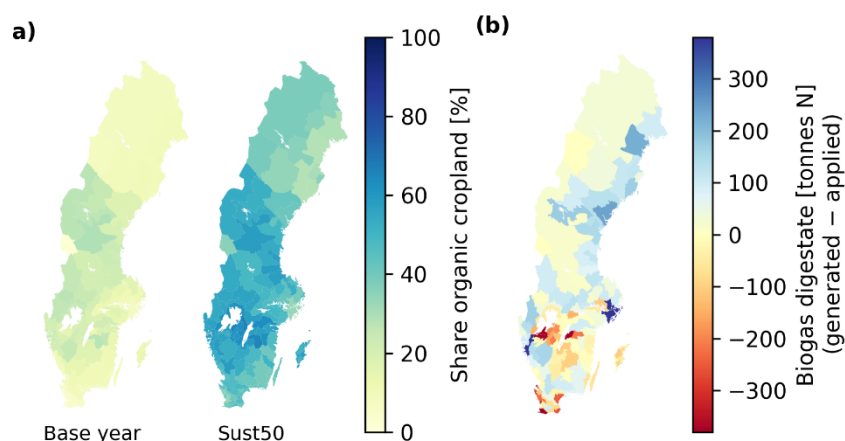
Figure 14. a) Share of cropland under organic production in the base year (2020) and in 2050 under the Sust50 scenario. b) Difference between generated and applied biogas digestate in terms of nitrogen (N) in the Sust50 scenario in 2050.

In summary, the results from the CIBUSmod modelling framework underscore the importance of considering nutrient flows in the agri-food system when evaluating scenarios for large-scale expansion of organic production. This aspect was not covered in the original analysis by Basnet *et al.* (2023), explaining the differences in results regarding land requirements and, consequently, in opportunities for carbon sequestration on "spared" cropland. It should however be noted that there are many options for enhanced nutrient supply in organic farming systems with limited land requirements that were not explored in this study. Such strategies could include increased recirculation of human excreta (Harder *et al.* 2019), introducing leguminous cover crops (Tribouillois *et al.* 2016) or harvesting nutrients from the sea (Spångberg *et al.* 2013). Furthermore, the Sust50 scenario was defined in CIBUSmod with an aim to reduce reliance on conventional animal manure in organic production. Allowing more conventional animal manure on organic cropland would reduce the need for green manures. But it would also increase mineral N fertiliser requirements, as animal manure would be redirected from conventional to organic cropland.

4   Discussion and conclusions

This paper presents a proof of concept for the CIBUSmod modelling framework. It demonstrates how input data can be collected and validated to establish a baseline. From this, scenarios involving different demand- and supply-side interventions can be developed and assessed.

While several similar models exist (e.g. Müller 2020; Kalt *et al.* 2021; van Selm *et al.* 2022; Jones *et al.* 2023), CIBUSmod offers key features that distinguish it from previous frameworks. Notably, it is open-source and provides a high degree of flexibility, allowing users to parametrise any number of regions, food items, crops, and livestock production systems. It also includes a detailed account of nutrient flows, as well as waste and food processing by-products, along with their end-use application in animal feed and energy recovery.

Although CIBUSmod is designed for modelling story-driven scenarios, it is relatively lightweight, enabling the exploration of "option spaces" that incorporate numerous scenarios with varying assumptions on key parameters such as crop yields, diets,

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and waste levels. This aligns with approaches used by Muller *et al.* (2017) and Kalt *et al.* (2021). This scenario development method has already been applied with CIBUSmod to assess the effects of reduced red meat intake recommendations in Sweden on land use, greenhouse gas emissions, and ammonia emissions (Slijper *et al.* 2024; Karlsson Potter *et al.* 2025). Additionally,
620   CIBUSmod allows for the decomposition of scenarios into their principal components, applying sets of parameter changes in sequence. This facilitates an analysis of the relative importance of different supply- and demand-side interventions within a given scenario.

Future work will build on this foundation, expanding the modelling framework as new research questions emerge. However, several known limitations and planned model developments already exist, as outlined in the following sections.

625   At present, land use and emissions are calculated only for domestic production, up to farm gate, including the supply chains for fertiliser and energy inputs. The model does not yet account for impacts arising from food processing and distribution. It also does not include impacts generated abroad, either directly through food and feed imports, or indirectly through exports. Import and export quantities are currently generated as outputs, and future development will focus on linking these to datasets that combine trade data with environmental impacts for traded food and feed commodities, such as the one developed for the
630   SAFAD tool (Röös *et al.* 2025) to quantify associated impacts. Alternatively, CIBUSmod outputs could be integrated with global-scale modelling frameworks, such as the one used by Mosnier *et al.* (2023).

For food processing, CIBUSmod accounts for material flows, including losses and generated by-products, but does not yet consider energy use in transports and processing beyond the farm gate. This omission can have significant impact when assessing scenarios that include a high proportion of novel or highly processed foods, such as meat analogues, where a large
635   share of environmental impacts are associated with energy use in processing (Mejia *et al.* 2020). Additionally, modelling scenarios that alter food processing—and therefore the quantity and quality of by-products, often used for animal feed—poses challenges in the current version. Currently, animal diets are input manually and any mismatch in supply and demand for by-products is corrected by adjusting imports and exports, or waste. To avoid this, feed rations would need to be manually refined to align with by-product supply in different scenarios, which is a tedious process often not practically feasible. However,
640   Wanecek (2025) presents an extension of CIBUSmod that incorporates feed rations into the optimisation problem, allowing them to be determined endogenously based on available feedstuffs and livestock nutritional requirements. This development will enable feed rations to respond dynamically to changes in by-product availability and composition under different scenarios, facilitating research on e.g. optimised use of local resources for animal feed.

In its current version, CIBUSmod models nutrient leaching from agricultural land only in terms of N leaching, using a basic
645   method that likely overestimates leaching in Sweden (see section 3.1.6) and does not directly account for management practices that reduce leaching. Future work will aim to incorporate improved methods to estimate both N and P leaching and runoff, incorporating regional differences in soil and climate while accounting for different management practices.

Changes in carbon stocks due to land use and land-use change are currently only modelled for organic soils, using emission factors for CO_2 and CH_4 per hectare. The version of the model presented here does not include changes in carbon stocks
650   resulting from shifts in agricultural land use or mineral soil organic carbon dynamics. A module that models changes in mineral

soil carbon stocks, based on carbon inputs from crop residues, manure, and other organic sources, using the ICBM model (Andrén *et al.* 2004) is however being developed and will be incorporated in future versions. Future work will also include modelling changes in soil and standing biomass carbon pools due to land use changes (i.e. expansion or retraction of agricultural land use).

655   At present, the model includes impact assessment methods for climate impacts, allowing users to select different approaches such as GWP, GTP, or time-dynamic climate impacts. Output also include land use and nutrient flows which readily allow the calculation of additional indicators for environmental impacts, such as "new N and P inputs" (Ran *et al.* 2024) or the application of methods to characterise biodiversity impacts from land use (e.g. Chaudhary & Brooks 2018). However, the capacity to identify trade-offs across multiple environmental and social sustainability dimensions is still limited. Future development will

660   expand the framework by incorporating additional impact categories and inventory models, including eutrophication, biodiversity impacts, animal welfare, and nutritional indices for diets.

To conclude, CIBUSmod provides an open-source, modular and spatially explicit framework for assessing national agri-food system scenarios supporting detailed analyses of land use, nutrient flows and emissions. The Swedish case study illustrates the model's capacity to reproduce baseline patterns and evaluate alternative scenarios. As such, CIBUSmod can hopefully offer a

665   practical and adaptable platform for researchers engaged in food systems sustainability analysis.

Code and data availability

The current version of CIBUSmod is available from the project's GitHub repository https://github.com/SLU-foodsystems/CIBUSmod under the GNU GPLv3 licence. The exact version of the model (v25.04) used to produce the results presented in this paper is archived on Zenodo under https://doi.org/10.5281/zenodo.15300943 (Karlsson *et al.* 2025), as are

670   datasets and Jupyter notebooks used to run the model and produce output figures. Additionally, instructions on installing, setting up the environment and running the model are provided via the repository's README file.

Author contribution

JOK was main responsible for model code development and for preparing the manuscript. JOK and HKP performed data collection and curation for the Swedish case study. OL developed the sub-model for estimating energy use in agricultural field

675   machinery. JOK, HKP, NE, RE and PAH were all involved in discussing model design during development. PAH supervised the work and acquired funding. All authors read and commented on the manuscript.

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Competing interests

680   The authors declare that they have no conflict of interest.

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