Sustainbeef

Indicator documentation

Deliverable 3.2

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ERA-NET SUSAN

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List of abbreviations

Abbreviation	**Explanation**
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
H_{eq}	Humus equivalent
LCA	Life cycle assessment
N	Nitrogen
N_2	Elemental nitrogen
NH_3	Ammonia
NH_{4+}	Ammonium
N2O	Nitrous Oxide
NO_3-	Nitrate
NO_x	Nitrogen Oxides
N-ORG	Organically bound nitrogen
N-TAN	Total ammonia nitrogen
P	Phosphorus
WP	Work package

Summary

The project Sustainbeef aims to co-define and evaluate sustainable beef farming systems based on resources non-edible by humans. Imbedded in the project is the work package 3: “Systems performance (modeling) and evaluation through indicators”. The report at hand discusses the implementation of different indicators for the system analysis using the single-farm model FarmDyn. The indicators are categorized according to the three dimensions of sustainability: environmental-, social- and economic dimension.

For the environmental dimension the methodology used follows the structure of an attributional life cycle assessment (LCA). Included are major emissions caused by agricultural practice in central Europe. Considered emissions and flows are methane from manure management and enteric fermentation, and nitrogen oxides, ammonia, and dinitrogen oxide from manure management and fertilizer use. Dinitrogen oxide stemming from crop residues, carbon dioxide from liming and particulate matter formation from cropping operations and animal husbandry are considered, too. Furthermore, on-field nitrogen losses through the leaching of nitrate and on-field phosphorus losses through leaching and runoff are calculated using advanced field-balances based on the well-known Agroscope LCA methodology SALCA Nitrat and SALCA Phosphor. Up-stream emissions through the provision of major farm inputs such as diesel, fertilizer, pesticides, farm machinery, and feedstuff are considered as industry standard emission factors taken from the literature. All other emissions are calculated model internally considering the model dynamics and farm heterogeneity in factor endowment and production patterns. The emissions are characterized into impact categories using factors from RECIPE 2016 including global warming, terrestrial acidification, marine and freshwater pollution, and particulate matter formation. Besides the LCA approach a humus balance is calculated for arable production to indicate potential humus and carbon losses from narrow crop rotations. All field-level emissions (nitrate leaching, phosphorus losses and humus balance) can be calculated using soil default values, where data on soil properties is missing, and with farm specific soil indices and relief profiles if available.

The economic sustainability on farm level is calculated as the profitability of the farm. The used indicators are the profit calculated as net present value (NPV) of the farm and gross margin calculated per animal and per grown crop. The gross margin is commonly used among practitioners and therefore easy to validate and compare. Furthermore, the autonomy of the farm is calculated but again, those indicators are strongly influenced by factors external to the model. For autonomy we calculate the dependence of the farm on external inputs (pesticides, fertilizer, and feedstuff) and subsidies, and the share of different income streams on the farms net income.

The assessment of the social dimension of sustainability is constrained by the scope and boundaries of the used methodology: As the modelling approach restricts the assessment to the farm level it is mainly viable to consider impacts on the farm-community. Calculated indicators are the total work load, the distribution of work over the year and the distribution of work by the type of work.

1 Introduction

The growing world population together with shifting consumption patterns lead to an increasing demand for animal products. As the feed for ruminant based animals is to a large extend grown on land, which could also be utilized for direct food production, the competition between feed and food is raised in social debates. In addition, livestock production systems cause various other adverse effects on the environment (Steinfeld 2006). Radiatively active gases such as methane, carbon dioxide and nitrous oxide, particulate matter formation and leaching of nitrogen and phosphorus are among such pollution of livestock production. Besides those adverse effects, beef farming systems can contribute to local employment and are sometimes part of the local cultural heritage. The dimensions affected by farming systems are three folded: the environment, the social and the economic sustainability can change through farming activities (Latruffe et al. 2016, p.123).

The project Sustainbeef searches for innovations to forego those potential tradeoffs and to improve the overall sustainability of beef production systems across Europe by defining and evaluating more sustainable beef farming systems that are based on resources non-edible for humans. The project is separated into four work packages (WP) that pursue different targets, from the characterization of representative beef production systems (WP2), the development of a multi-criteria assessment methodology (WP2), the system performance evaluation (WP3), identification and definition of innovations (WP4) and the evaluation of the innovation's impacts at territorial and value chain scale (WP4). The different WPs are executed by teams from five countries and eight institutions. Each team contributed a set of typical farms for their region yielding in farm types for nine regions from France, Belgium, Italy, and Germany.

The WP 3: "Systems performance (modeling) and evaluation through indicators" aims to assess the performance of different beef production systems. For the assessment the modeled case study farms will be given the opportunity to include the innovations as pre-defined in different scenarios and then compared to a baseline. As a starting point for analysis, the single farm model FarmDyn is utilized (Britz et al. 2014). Due to the impact level and high degree of detail of the innovations to be analyzed and the heterogeneity in the farm sample farm level modelling is a well-suited methodology to assess the sustainability of the systems and innovations.

The report at hand documents the development and implementation of indicators as deliverable 3.2 of WP 3. The report builds up on the work package 2 "development of a multi-criteria assessment methodology" and serves as a foundation for work step 3.4 "System performance evaluation".

The work is structured as follows: In the beginning of the report the selection criteria and the indicator requirements are discussed. Then, the model characteristics of FarmDyn that are important for the indicator implementation are shortly presented. After that, the indicators implemented in FarmDyn are described, structured by the three pillars of sustainability, first the environmental indicators are discussed, subsequently the economic indicators are presented and thirdly, and finally the social indicators are outlined.

2 Indicator selection and interpretation

The selection of indicators substantially influences the drawn conclusions. In order to generate scientifically sound results that are meaningful for practitioners and decision makers the identification, selection and reporting is of great concern. A preliminary indicator selection was conducted in the work package 2.2 (WP2.2). The related deliverable is completed parallel to the deliverable at hand. Due to the model boundaries, the preselected indicators have to be further stripped down.

All indicators have to be applicable to the model in some form. If the input data for the indicator calculation is part of the output of FarmDyn the indicator is potentially applicable. The application then can be conducted in two forms: model internal, meaning the indicator is computed as part of the optimization problem, or post model, meaning the indicator is calculated based on the model results. Both approaches have their advantages and disadvantages: The internal calculation of the indicators bares mathematical restrictions depending on the technical realization of the model. In the case of FarmDyn the technical realization is conducted as a mixed integer programming optimization model meaning that all equations that are part of the optimization have to be linear. The calculation of indicators post model has no such restrictions but is not usable for extended analysis, for example the estimation of abatement costs or the implementation of emission caps or taxes. Information on which indicator is calculated with which methodology is given in the respective indicator description.

Furthermore, the sample of typical beef producing farms requires flexibility in the parameterization to incorporate local conditions while keeping a level of simplicity to be usable within a reasonable workload. Especially the data acquisition for the parameterization of some indicators can be time intensive. This oftentimes restricts not only the indicator itself but the methodology to calculate it. There is always a compromise between level of detail, simplicity and explanatory power. Even if an indicator is applicable it is not necessarily significant. “Essentially, all models are wrong, but some are useful”, George E. Box once stated. This is also true for the FarmDyn model: essentially all modeled indicators are “wrong” but given a precautious approach in interpreting them some can be useful in ex-ante impact assessment of innovations and policy scenarios. Others that are relying on model exogenous assumptions or indicators that are highly aggregated might not be viable in predicting changes due to innovations or do not capture the most important impacts of an innovation. To prevent misinterpretation of indicators or drawing the wrong conclusion such indicators are left out. Further limitations and stepping stones in calculation and interpretation are highlighted in the description of the respective indicators. The reduced evaluation tree for FarmDyn can be seen in Figure 1.

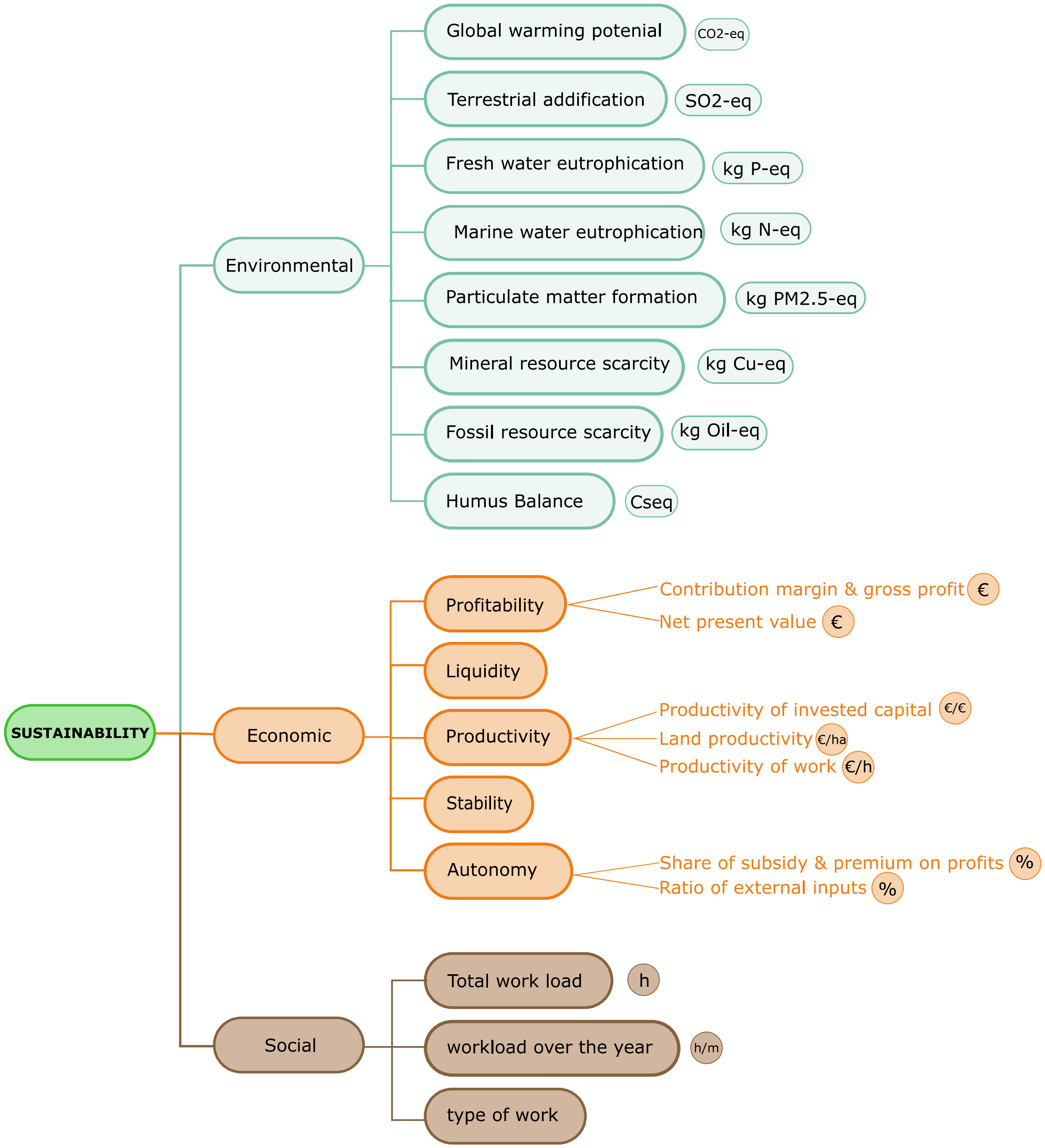

Figure 1: Evaluation tree for FarmDyn
Source: Own illustration

3 The model FarmDyn

The system performance analysis and assessment of innovations is conducted with the single farm optimization model FarmDyn. The model originates from a research project financed by the German Science foundation. The aim was to measure greenhouse gas abatement costs of German dairy farms. Further extensions have been made to the model (Garbert 2013, p.94; Remble et al. 2013 p.2 ff). At the moment several research projects are working with different compartments of the FarmDyn model.

The model is realized as a flexible modular template design optimization model. The framework enables simulations of farm management and investment under changing conditions, for example price changes, policy interaction or differing environmental conditions. The model optimizes the NPV of a defined farm or farm sample via Mixed Integer Programming. Mixed Integer Programming is used to include indivisibilities in investments into farm assets or other things which are not depictable by classic linear optimization models. Constraints that are restricting the simulated farm are dividable into (1) the production feasibility set of the farm with biophysical interactions, (2) maximal willingness to work of the family members for working on and off farms, (3) liquidity constraints, and (4) environmental restrictions. Currently, the model is parameterized to German conditions (Britz et al. 2014).

Of particular importance for the case at hand are the bio-physical relationships between emissions and agricultural practice, as well as the associated costs and workload. Key elements for the assessment are the representation of the herd, feeding activities, manure handling and on-field activities, for e.g. fodder production, as these are meant to have the greatest impact on the analyzed indicators. The representation of those elements in FARMDYN is explained in the following.

The herd demographics are captured in monthly resolution. Herds are differentiated using age, gender, breeds and production objective. Cattle herds are further broken down into cows, heifers, male and female calves, for different feeding regimes and production intensities, defined by daily weight gains and milk yield. The herds are adjusted dynamically with consideration of new born animals and the raising process up to the stage of heifers or young bulls. Heifers can then be further fed with different intensities and therefore different production lengths until they enter the active dairy herd. Accordingly, the age of first calving and the overall production length is determined by prior feeding strategies. Heifers can also be bought from the market. If viable animals can leave the herd and be slaughtered/ sold to the market at the end of their actual production phase.

The feeding of the herd is constrained by various nutritional requirement functions. These functions consider energy requirements, maximum dry matter intake, maximum/minimum dry matter shares from roughages and concentrates, maximum starch and sugar shares as well as the ruminal nitrogen balance of the animals. The requirements are adapted throughout the lactation phase of a cow, or growing phases of other cattle. In order to fulfill the requirements, different feeding activities link the on-farm grown fodder to the animals. Additionally, different varieties of fodder and concentrates can be bought from the market. The feed-mix eventually chosen by the model is composed to be cost efficient while ensuring the metabolic constraints of the specific animal category.

The manure module comprises the management of manure on the farm including animal excretion, storage and application of manure. Manure excretion is based on fixed factors considering animal types, yield levels and feeding practice and accounts for organic N, total ammonia N, P and total volume. The manure can then be stored in a subfloor-storage under the stable or in outside silos with different cover options. If animals are grazing, the excretion on pastures is considered in an own pool with similar nutrient sub pools. Further constraints ensure minimum requirements for storage capacity and a complete emptying of the storages in spring. Manure application is conducted via contracting with several optional application techniques such as drag hose, broad spreader or injection.

On-field activities are managed by the crop module and the grassland module. The agricultural land endowed by the farm is separated in arable land, grassland and permanent pastures. The on-field activity is restricted by land availability, variable costs, yields, machinery and fertilizer use, and available field working days. The grassland can be used as pastures or for fodder production with different intensities (fertilization, number of cuts) and hence different yields. Crop rotational constraints are realized as maximum shares.

The depiction of labour on the farm considers a fixed amount of work for general administrative work not depending on farm branches or farm size, management work depending on the size of the different farm branches, and labour need for different farm operations in stables and on fields. Furthermore, the possibility of off-farm work can be chosen. Labour need for animals varies by animal type and stable size while labour need for field activities varies by crop, month, and fertilizer type and amount applied. Additionally, the availability of field working days limits the number of days where specific field operations are possible due to climatic or soil conditions.

The current state of the model inherits plenty adaptations in order to depict the characteristics of the SustainBeef farm types and the properties of the defined innovations. A detailed, up-to-date description of the model and all its features can be found in the new online model documentation[1].

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[1] http://www.ilr.uni-bonn.de/em/rsrch/farmdyn/farmDynDoku/

4 Environmental Indicators

The framework for assessment of the environmental sustainability of production systems and innovations follows commonly applied methodology. The structural concept broadly follows the principles of Life cycle assessment (LCA) as laid down in ISO 14040 and ISO 14044. According to this, the basic steps of an LCA are the definition of goal and scope, the inventory analysis, the impact assessment and interpretation. The structure is depicted in Figure 2. As the underlying report is rather a documentation of the proposed and applied methodology it follows the structure only where possible.

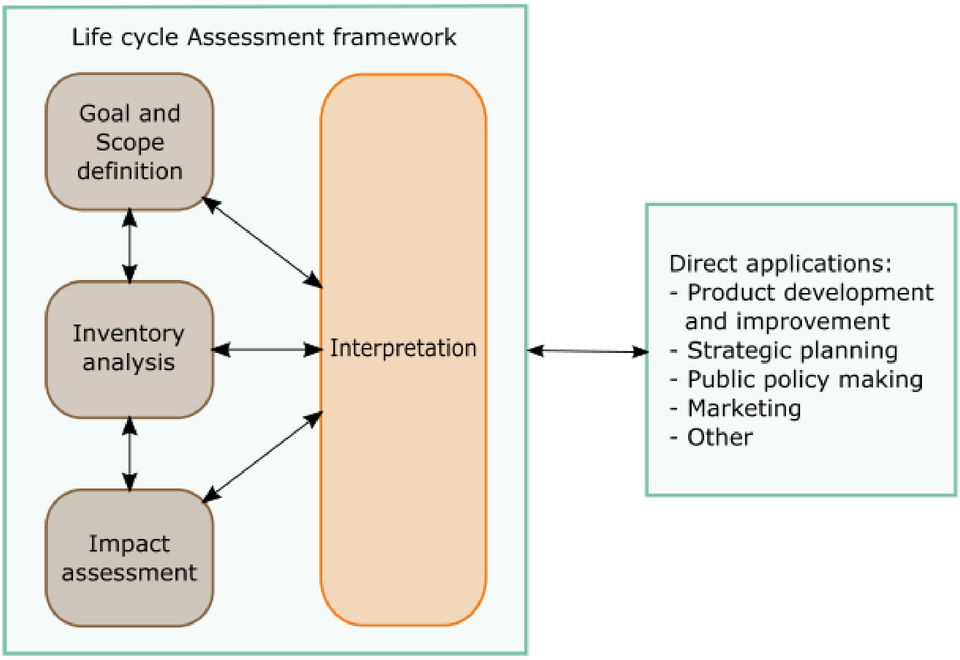

Figure 2: Elements of the LCA framework and possible applications of the results
Source: own illustration based on ISO 14040

4.1 Goal and scope

The goal of the deliverable is to assess the sustainability of beef production systems and the potential influence of innovations on farm performance at farm level using a farm level optimization model. The geographic scale is set to a sample of case study farms across Europe including farms in France, Germany, Italy and Belgium that are meant to be representative for specific regions and production systems. The results of the assessment of the different case study farms can be useful for policy design and practitioners along the value chain, as they provide insights into the effects of various innovations and the actual performance and issues of these farms.

To capture the differences of the heterogeneous sample, the scope is set from cradle to farm gate, including feed production, cow-calf and fattening operations. Up-stream emissions and impacts are considered for mayor farm inputs; machinery, diesel, fertilizer, pesticides, feedstuff, and energy. The considered emissions and the respective source of emissions of both on farm and of farm emissions are depicted in Figure 3.

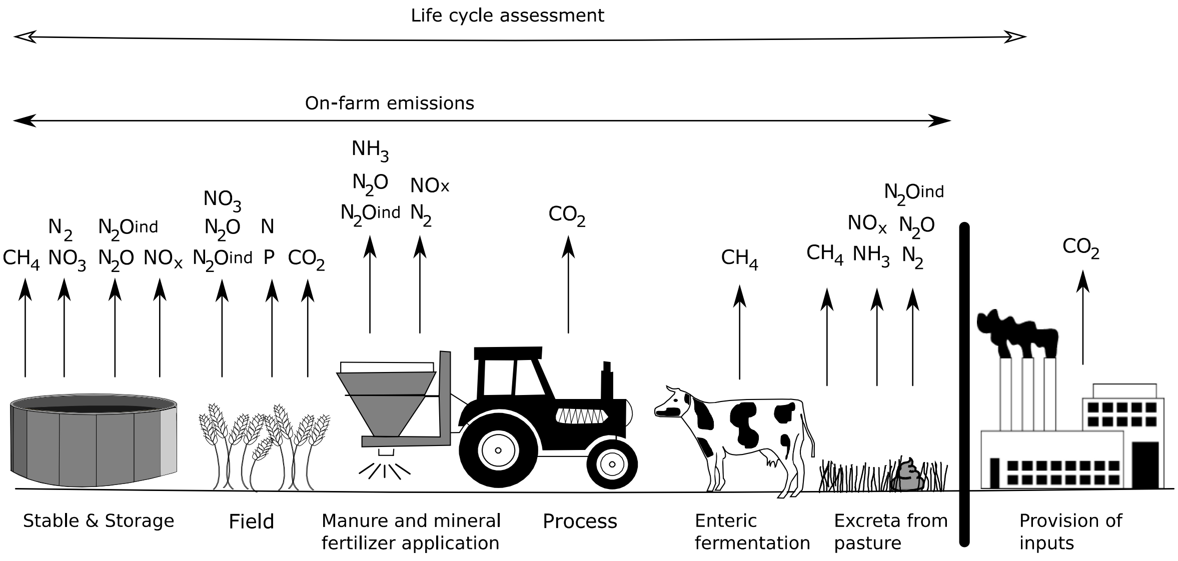

Figure 3: Emissions considered in the LCA and their source. Including on farm and off farm emissions. Source: own illustration

While cattle and farm data are collected farm specific for the modeled case study farms, data for inputs is taken according to industry standards. Long-term investments and assets such as stables and sheds are disregarded in the underlying assessment. The model's time dynamic is comparative static, which implicates continuous reinvestment in such assets and hence no changes in the infrastructure over time. Therefore, emissions related to the building of the farm infrastructure are not included. Nevertheless, those emissions commonly have an insignificant impact on overall the results.

Limitations in the emission assessment arise from the modeling approach: Due to the further usage of the model to calculate, inter alia, abatement costs, all emission accounting is supposed to be model internal. In contrast to a post-model calculation of emissions, all equations have to be adjusted to the requirements of the underlying optimization procedure of the model. In the case of FarmDyn the mathematical requirements are that all equations are linear.

4.2 Functional unit and allocation

The functional unit was defined as emissions per kg beef carcass produced. The dressing percentage used to calculate the carcass yield represents animal characteristics (gender, age and breed). Additionally, emissions are related to other units, namely emissions per ha, per kg of total proteins and per produced calorie.

In some case studies beef production is a co-product or by-product, for example in arable-mixed farming or as a by-product on dairy farms. In those cases, not all emissions on farm can be related to the beef output. For reasons of consistency and comparability between the systems and farms allocation of emissions between the different products is applied. The considered allocation method applied is economic allocation based on market prices of final products, allocation based on calorie output and based on protein output.

4.3 Inventory analysis

In the following section the application of the methodology in FarmDyn is presented. All equations and the related parameters, variables and indices are named similar to the actual code in FarmDyn. The parameter values and emission factors used, and the set names and elements related to the environmental accounting are depicted in annex I – II.

4.3.1 Gaseous emissions

Agricultural practice leads to gaseous emission of a manifold of gases that eventually impact the environment through different pathways and impact categories. Arguably the most important gases emitted through cattle farming are methane (CH_4), ammonia (NH_3), nitrous dioxide (N_2O), nitrogen oxides (NO_x) and carbon dioxide (CO_2). Naturally, those gases are considered in the environmental impact assessment at hand. In the following the sources, pathways and impacts of the respective gases are elucidated. Based on this information a methodology is proposed.

4.3.1.1 Methane

CH_4 is a radiatively active gas resulting from manure management and enteric fermentation. In this context manure management includes the storage, processing and the disposal of manure. CH_4 originates from the transformation of the organic substance of manure under anaerobic conditions. The CH_4 emission rate therefore depends on the amount of manure produced and the respective portion that decomposes anaerobically. Dung on stable floors or pastures is exposed to more aerobic conditions compared to slurry pits resulting in lower CH_4 emissions (Dong et al. 2006, p.10.35).

The calculation of CH_4 emissions stemming from manure storage $E_{CH4,ManureStorage}$ in kg CH_4, are calculated according to Dong et al. (2006) p.10.41. The manure volume from different animal categories in m^3 in the different storage systems, *v_volInStorageType* is the activity data used to estimate emissions. The number of volatile solids in the slurry is estimated based on *v_volInStorageType* in m^3 using the average dry matter in %, *p_avDmMan*, and the share of volatile solids in the dry matter in %, *p_oTSMan*. The effect of different slurry cover types on emissions is incorporated via different methane conversion factors, *p_MCF, in % of volatile solids*. Furthermore, several manure types are considered in the maximum CH_4 producing capacity in m^3 kg^{-1}, *p_BO.* The emission factor is divided by 12 to account for the monthly resolution:

$$E_{CH4,ManureStorage} = sum(\ (curManChain, manStorage), v_{volInStorageType(curManChain,manStorage,t,nCur,m)} * 1000 * p\_avDmMan(curManChain) * p\_oTSMan(curManChain) * p\_BO(curManChain) * p\_densM * p\_MCF(Manstorage, curManChain)\ /12) \quad (1)$$

CH_4 emissions from manure excreted on pastures are calculated analogue to those from stored manure. In line with the previous approach, a specific MCF value (*p_MCFPast*) and instead of the volume of stored manure, the volume of manure excreted on pastures is used (*v_manQuantPast).*

Enteric fermentation refers to the digestive process of decomposition of carbohydrates into simple molecules through micro-organisms in the digestive system of herbivores. The process enables the absorption of the decomposed carbohydrates into the bloodstream of the respective animal. CH_4, in this process, is produced as a byproduct resulting from fermentation. Enteric fermentation is particularly important for ruminant livestock, such as cattle: Their expansive rumen is especially suited for microbial fermentation and enables ruminants to digest even cellulose. Significant influences on the emission level of CH_4 are the quantity, quality and composition of the feed intake, the type of digestive tract, and the age and weight of the animal (Dong et al. 2006, p.10.24).

Emissions from enteric fermentation, $E_{CH4,EntericFermentation}$ in kg CH_4, are calculated based on Dong et al. (2006) p.10.31. The actual feed intake of different herds, *v_feeduse*, measured in gross energy is the activity data used to calculate emissions. CH_4 conversion factors, *p_Ym*, represent animal specific emission rates in % of gross energy converted to methane. 55.65 (MJ (kg CH_4)$^{-1}$) is the energy content of methane. Again, the emission factor is divided by 12 to account for the monthly resolution. Down below, the calculation for emissions from enteric fermentation of dairy cows is depicted as an example:

$$E_{CH4,EntericFermentation} = sum((feeds, dcows, n), p\_feedContFMton(feeds, "GE") * v\_feedUseHerds(dcows, feeds, t, n) * p\_Ym("dcows"))/(100 * 55.65) \quad * 1/12) \quad (2)$$

4.3.1.2 Nitrogen emissions

Gaseous N emissions originate from nitrification, denitrification and ammonification. The interplay of the mentioned processes and other forms and pathways in the environment are commonly depicted in the so-called N cycle as depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.**4.

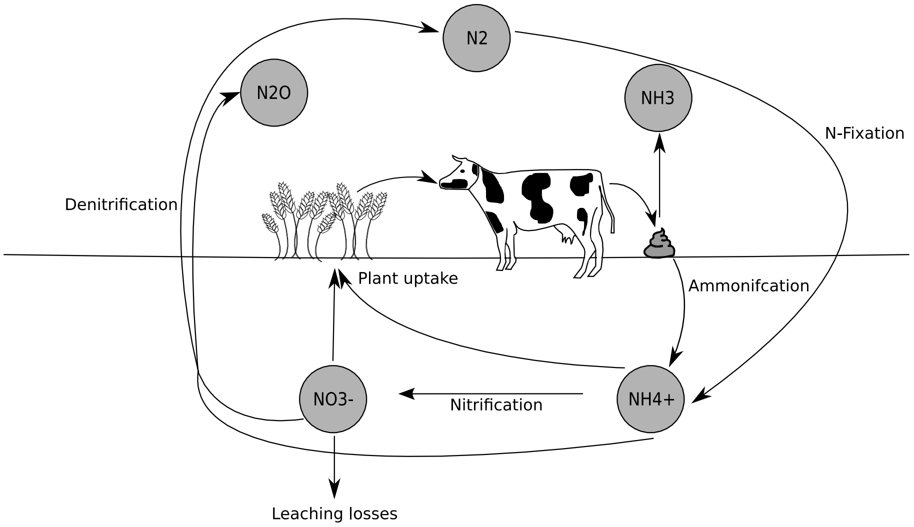

Figure 4: N cycle depicted for the example of cattle
Source: Own illustration

Nitrification is the oxidation of ammonium (NH_{4+}) to nitrate (NO_{3-}). In the process of denitrification NO_{3-} is reduced to elemental nitrogen (N_2). N_2O and NO_x are co- and intermediate products of nitrification and denitrification (Klein et al. 2006, p. 11.5). Ammonia is emitted in the process of ammonification, i.e. the breakdown of reduced organic N to NH_{4+}.

Further distinction in the emission of N_2O is in the pathway of the N cycle: in some cases, N first has to leave a system or bond to be part of the N cycle. Degassing, runoff or eluviation can be preliminary steps for N to be part of the processes of nitrification and denitrification. Emissions of N_2O from those pathways are attributed to indirect emissions (Dong et al. 2006, p.10.52). In agriculture gaseous N emissions occur mainly during manure management and fertilizer application.

Nitrogen (N) based emissions are calculated using a mass-flow approach starting with the N excretion by farm animals and the application of artificial fertilizer. Three N-pools are considered, total ammonia N (N-TAN), organically bound N (N-Org) and the total N pool consisting of the latter two. The N mass-flow approach is depicted in Figure 5 down below:

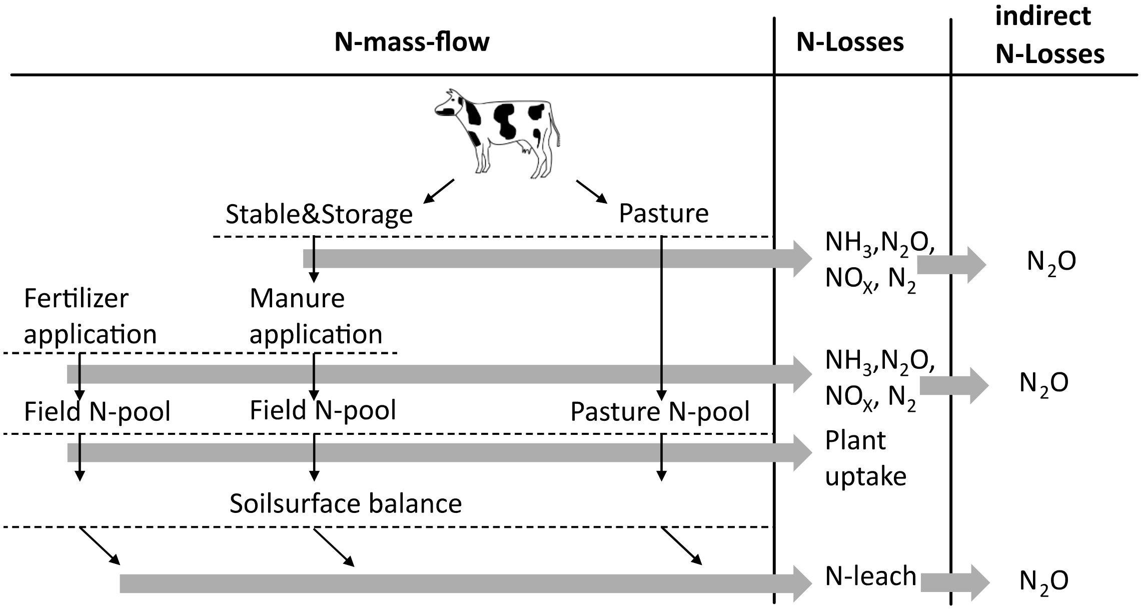

Figure 5: N mass flows and the resulting N losses originating from cattle.
Source: Own illustration

NH_3 emissions ($E_{NH3,stableStorage}$ in kg NH_3-N) at the stable stage are calculated according to the N-TAN in manure as excreted by the animals, *v_nut2ManureM,* in kg N-TAN. NH_3 emissions from storage are calculated based on the N-TAN pool in storage, *v_nutPoolInStorage,* in kg N-TAN. The emission factors differentiate between cattle and pig slurry. While NH_3 emissions are only based on the N-TAN pool, other N emissions are based on the total N pool as depicted in *v_nut2manureM, too*. Considered emissions are N_2O and NO_x. N_2 is generally not considered as an emission. For the completeness of the N-flow model N losses in the form of N_2 are still calculated in the environmental accounting. Indirect N_2O emissions (N_2Oind) are calculated based on prior emissions of reactive N species, namely NH_3, NO_x and NO_{3-}. For the sake of simplicity, the stages stable and storage are summarized in the calculation of emissions. The emission factor accordingly is named *p_EFStaSto*. Compared to total N_2O and NO_x emissions on farm the emissions at this stage are rather small and the generalization is not expected to distort the results. N emissions from stable and storage are calculated based on Haenel et al. (2018) p. 50 f., and EMEP (2016) 3.B p. 20 ff.:

$$\begin{aligned} E_{NH3,StableStorage} &= sum(sameas(curManChain, curChain), \\ &\quad v\_nut2ManureM(curManChain,\mathrm{NTAN}, t, nCur, \mathrm{m}) * \mathrm{p}\_EFSta(\mathrm{NH3}) \\ &\quad + v\_nutPoolInStorage(curManChain,\mathrm{NTAN}, t, nCur, m) * p\_EFSto("NH3")) \end{aligned} \quad (3)$$

Other N_2O, NO_X and N_2 emissions ($E_{N2O,StableStorage}$ in kg N) from stable and storage are calculated analogue to the example of N_2O emissions in the following:

$$E_{N2O,StableStorage} = sum(sameas(curManChain, curChain), (v\_nut2ManureM(curManChain, "NTAN", t, nCur, m) + v\_nut2ManureM(curManChain, "NOrg", t, nCur, m)) * p\_EFStaSto("N2O", curManChain)) \tag{4}$$

Indirect N_2O emissions from stable and storage ($E_{N2Oind, StaSto}$) are calculated as follows. Note that the emission factor for indirect N_2O emissions is always named *p_EFN2Oind*:

$$E_{N2Oind,StableStorage} = sum(sameas(curManChain, curChain), \mathrm{v}\_emissions(curChain, \mathrm{stasto}, \mathrm{NH3}, t, nCur, m) + v\_emissions(curChain, "stasto", "NOx", t, nCur, m)) * p\_EFN2Oind \tag{5}$$

The calculation of N emissions from pastures follows the same logic as the calculation of emissions from the stable and storage stage. The emission factors, *p_EFpasture*, represent the conditions of manure excreted on pastures. The source of the applied methodology can be found in EMEP (2016) 3.B p. 20 f. and Klein (2006)-11.6 f.

For NH_3 emissions from pastures ($E_{NH3,Past}$):

$$E_{NH3,Past} = sum(c\_s\_t\_i(past, plot, till, intens), v\_nut2ManurePast(past, plot, till, intens, "NTAN", t, nCur, m) * p\_EFpasture("NH3")) \tag{6}$$

For other direct gaseous N emissions from pastures at the example of N_2O ($E_{N2O,Past}$):

$$E_{N2O,Past} = sum(c\_s\_t\_i(past, plot, till, intens), (v\_nut2ManurePast(past, plot, till, intens, "NTAN", t, nCur, m) + v\_nut2ManurePast(past, plot, till, intens, "Norg", t, nCur, m)) * p\_EFpasture("N2O")) \tag{7}$$

Indirect N_2O emissions from stable and storage ($E_{N2Oind, Past}$) are calculated as follows:

$$E_{N2Oind,Past} = (v\_emissions(" ", "\mathrm{past}", \mathrm{NH3}, t, nCur, m) + v\_emissions(, \mathrm{past}, \mathrm{NOx}, t, nCur, m)) * p\_EFN2Oind \tag{8}$$

NH_3 emissions from the application of manure, $E_{NH3, ManureApplication}$ in kg NH_3-N, are calculated based on the N-TAN pool in the slurry leaving the storage stage. The amount is estimated using the total amount of slurry in m^3 *v_manDist* and the amount of nutrients in the slurry as determined by *p_nut2inMan* in kg N-TAN. The emission factor vary between grassland and arable land, different application devices and pig and cattle slurry. The methodology applied is adapted from EMEP (2016) 3.B p.25:

$$\begin{aligned}
&E_{NH3,ManureApplication}\\
&\quad = sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens),\\
&\qquad\quad manApplicType\_manType(ManApplicType, curManType)),\\
&\qquad v\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m)\\
&\qquad\quad *\ sum(manChain, p\_nut2inMan(\text{"}NTAN\text{"}, curManType, manChain))\\
&\qquad *\ (1 -\ p\_nut2UsableShare(crops, curManType, manApplicType, \text{"}NTAN\text{"}, m)))
\end{aligned} \tag{9}$$

N_2O, NO_x and N_2 emissions of manure application are calculated based on the total N pool at the application stage, *v_nut2manApplied* in kg N. The emission calculation is depicted using the example of N_2O emissions, $E_{N2O,\ ManureApplication}$ in kg N_2O-N, in the following. The emission factor (p_EFAPpplMin in kg N_2O-N (kg N)$^{-1}$ is equal to the emission factor for the application of synthetic fertilizers, as proposed by Haenel (2018) p.327. The calculation of N_2O emission follows Klein (2006)-11.7, the calculation of NO_x EMEP (2016)-3.B-11 and N_2 from Rösemann (2015) p. 317:

$$\begin{aligned}
&E_{N2O,ManureApplication}\\
&\quad = sum((sameas(curManChain, curChain), nut2)\ ,\\
&\qquad v\_nut2ManApplied(curManChain, nut2, t, nCur, m)\ *\ p\_EFApplMin(\text{"}N2O\text{"})\ )
\end{aligned} \tag{10}$$

Indirect N_2O emissions, $E_{N2Oind,\ ManureApplication}$ in kg N_2O-N, are based on prior emissions of NH_3 and NO_x:

$$\begin{aligned}
&E_{N2Oind,ManureApplication}\\
&\qquad = sum(sameas(curManChain, curChain)\ ,\\
&\qquad\qquad v\_emissions(curChain, \text{"}manAppl\text{"}, \text{"}NH3\text{"}, t, nCur, m)\\
&\qquad\qquad +\ v\_emissions(curChain, \text{"}manAppl\text{"}, \text{"}NOx\text{"}, t, nCur, m))\\
&\qquad\qquad *\ p\_EFN2Oind
\end{aligned} \tag{11}$$

N-emissions from the application of mineral fertilizer application, except NH_3, follow the same logic as from the application of manure. The calculation of N_2O emission follows Klein (2006)-11.7, the calculation of NO_x EMEP (2016)-3.B-11 and N_2 from Rösemann (2015) p. 317. The emission of NH_3 from mineral fertilizer application are calculated for different fertilizer types according to EMEP (2016)-3.D p.161. For the calculation of emissions only the emission factor changes from p_EFApplMinNH3 in kg NH_3-N (kg N)$^{-1}$ to *p_EFApplMin* in kg. N_2O-N (kg N)$^{-1}$. The pool of applied N from mineral fertilizer is determined by the total amount of applied fertilizer *v_syntDist* in kg multiplied by the share of N in the fertilizer, *p_nutInSynt* in kg N (kg fertilizer)$^{-1}$. In the following the emission calculation is depicted at using the example of NH_3 emissions, $E_{NH3,\ MineralApplication}$ in kg NH_3-N:

$$\begin{aligned}
&E_{NH3,MineralApplication}\\
&\quad = sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens), syntFertilizer),\\
&\qquad\quad v\_syntDist(crops, plot, till, intens, syntFertilizer, t, nCur, m)\\
&\qquad\qquad *\ p\_nutInSynt(syntFertilizer, \text{"}N\text{"}\ )\\
&\qquad\qquad * p\_EFApplMinNH3(syntFertilizer)\ )
\end{aligned} \tag{12}$$

Indirect N_2O emissions from mineral fertilizer application, $E_{N2Oind,\ MineralApplication}$ in kg N_2O-N, are based on prior emissions of NH_3 and NO_x:

$$\begin{aligned}
&E_{N2Oind,MineralApplication}\\
&\quad = sum(sameas(curManChain, curChain)\ ,\\
&\qquad\quad v\_emissions(curChain, \text{"}minAppl\text{"}, \text{"}NH3\text{"}, t, nCur, m)\\
&\qquad + v\_emissions(curChain, \text{"}minAppl\text{"}, \text{"}NOx\text{"}, t, nCur, m))\ *\ p\_EFN2Oind
\end{aligned} \tag{13}$$

The calculation of N_2O emissions from crop residues is divided into three parts: At first the above and below ground N pool from crop residues is determined. Then the removal of N in crop residues through the harvest of straw is deducted. In a last step the remaining N pool is multiplied with an emission factor. The methodology is adapted from Klein (2006)-11.11 ff. The parameter *p_cropResi* inherits all further information needed for the derivation of the amount of N in crop residues. The different information is controlled through the set *resiEle*. The parameter includes information about the duration of cropped system (“*duration*”), the frequency of harvesting (“*freqHarv*”), the dry matter content of the fresh matter yield (“*DMyield*”), the dry matter content of above ground residues (“*DMresi*”), the ratio of above ground crop residues to yield (“*aboveRat*”), the nitrogen content of the above-ground crop residues (“*aboveN*”), the ratio of below ground crop residues to above ground biomass (“*belowRat*”), and the nitrogen content of below ground crop residues (“*belowN*”). At first the above ground N from organic material, $N_{aboveGround}$ in kg N, is calculated based on the main output, which is determined by the cropped area *v_cropHa* in ha multiplied by the main output of the respective crop *p_OCoeffC* in t fresh matter ha^{-1} of the respective crop:

$$
\begin{aligned}
&N_{aboveGround} \\
&\quad = v\_cropHa(crops, plot, till, intens, t, nCur) \\
&\qquad * sum(\ (plot\_soil(plot, soil), curProds), \\
&\qquad\qquad p\_OCoeffC(crops, soil, till, intens, curProds, t)) \\
&\quad * p\_cropResi(crops, "duration") * p\_cropResi(crops, "\mathrm{freqHarv}") \\
&\qquad\qquad * p\_cropResi(crops, "aboveRat") * p\_cropResi(crops, "aboveN")
\end{aligned}
\tag{14}
$$

Then the below ground N, $N_{belowGround}$ in kg N, from organic matter is calculated, again based on the main output of the respective crop. A conditional assignment *($(not sameas(crops,"potatoes") and not sameas(crops,"sugarBeet"))*) includes a slightly different calculation for root and tuber crops due to their characteristics of having the main harvested crop parts below ground.

$$
\begin{aligned}
&N_{belowGround} \\
&\quad = v\_cropHa(crops, plot, till, intens, t, nCur) \\
&\qquad * sum(\ (plot\_soil(plot, soil), curProds), \\
&\qquad\qquad p\_OCoeffC(crops, soil, till, intens, curProds, t)) \\
&\quad * p\_cropResi(crops, "duration") * p\_cropResi(crops, "\mathrm{freqHarv}") \\
&\quad * (\ p\_cropResi(crops, "DMyield")\$(not\ sameas(crops, "potatoes") \\
&\qquad\qquad and\ not\ sameas(crops, "sugarBeet")) \\
&\quad + p\_cropResi(crops, "aboveRat") * p\_cropResi(crops, "DMresi")) \\
&\qquad\qquad * p\_cropResi(crops, "belowRat") * p\_cropResi(crops, "belowN")
\end{aligned}
\tag{15}
$$

The calculated N pool from organic crop residues is deducted by N that is removed with straw, $N_{strawRemoval}$ in kg N. To calculate this N removal the variable *v_residuesRemoval* (cropped area from which straw is removed in ha), the parameter *p_OCoeffResidues* (removed straw in t ha^{-1}) and the parameter *p_nutcontent (*nutrient content of residues in kg n t^{-1}) are utilized:

$$
\begin{aligned}
&N_{strawRemoval} \\
&\quad = sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens))\ , \\
&\qquad\qquad v\_residuesRemoval(crops, plot, till, intens, t, nCur) \\
&\qquad\qquad * sum(\ (plot\_soil(plot, soil), curProds), 10 \\
&\qquad\qquad * p\_OCoeffResidues(crops, soil, till, intens, curProds, t)) \\
&\qquad\qquad * \ p\_nutContent("winterBarley", "WBresidues", "N"))
\end{aligned}
\tag{16}
$$

The total N-pool from remaining crop residues is multiplied with the emission factor *p_EFApplMin("N2O")* (in kg N_2O-N(kg N)$^{-1}$) to gain the total emissions of N_2O, $E_{N2O,Residues}$ in kg N_2O-N:

$$N_{strawRemoval} = (N_{aboveGround} + N_{belowGround} - N_{strawRemoval}) * \mathrm{p\_EFApplMin(“N2O”)} \tag{17}$$

4.3.1.3 Carbon dioxide from liming

Lime is commonly used in agriculture to manage soil acidity. Soil acidity is important to manage the availability of nutrients and mineralization and is therefore crucial for plant growth. The carbonated lime dissolves into CO_2 and water (Klein 2006, 11.26). To calculate the emissions from liming, $E_{CO2,Liming}$ in kg CO_2, the amount of applied lime is paired with a simple emission factor, as proposed by Klein (2006, 11.27). The amount of applied lime is determined from the bought inputs, *v_buy* in t. The emission factor *p_EFLime* in kg CO_2 (t of lime)$^{-1}$.

$$E_{CO2,Liming} = sum((curInputs(inputs), sys), v\_buy(inputs, sys, t, nCur) * p\_EFLime(inputs)) \tag{18}$$

4.3.1.4 Particulate matter formation

The impact category particulate matter formation refers to the suspension of microscopic matter into Earths' atmosphere. The particles can adversely affect human health. The main sources of agricultural emissions are soil cultivation and harvesting. (EMEP 2016 3D p.8) and animal housing (Haenel et al. 2018, p.67). Indirect emissions can form from prior NH_3, NO_3 and NO_X emissions (WHO 2003). In EMEP (2016) particulate matter emissions are categorized into three compartments depending on the size of the particles: particulate matter smaller than 2.5 µm ($PM_{2.5}$), particulate matter smaller than 10 µm ($PM_{2.5}$) (PM_{10}) and total suspended particles (TSP). Although all compartments are calculated in FarmDyn only the smallest particles ($PM_{2.5}$) enter the later characterization step according to Huijbregts et al. (2016) (see Chapter 4.4).

The calculation of NH_3 and NO_X is described above while emissions of NO_{3-} are described in the chapter 4.3.2. Direct emissions of particulate matter from animal husbandry are calculated according to EMEP (2013) 3.3 using a tier 2 approach considering different animal types, stable systems and the time animals spend in the stable. As stable systems are considered as an exogenous decision in the model, an emission factor (*p_EFpmfHerds* in kg particulate matter head^{-1}) is linked to the variable *v_herdsize* in head month^{-1}:

$$\begin{aligned} &E_{PMF,Stable} \\ &\quad = sum((herds, breeds, feedregime, stableStyles, sameas(curmanchain, curChain)), \\ &\qquad v\_herdSize(herds, breeds, feedRegime, t, nCur, m) \\ &\qquad * \ p\_EFpmfHerds(herds, feedregime, curmanchain, emissions)\ ) \end{aligned} \tag{19}$$

Direct emissions of particulate matter from crop cultivation, harvesting and processing are calculated according to EMEP(2016) 3D p.19 considering the type of crop, the crop specific cultivation operations, harvesting operations and the storage and processing of harvested goods (drying and cleaning). The respective emission factor, *p_EFpmfCrops* in kg particulate matter ha^{-1}, can incorporate the effect of climate, too. *P_EFpmfCrops* is build up on the exogenously determined crop operations. The activity data entering the equation is the cropped area per crop, *v_cropHa* in ha crop^{-1}:

$$\begin{aligned} &E_{PMF,Field} \\ &\quad = sum((c\_s\_t\_i(curCrops(crops), plot, till, intens), operation), \\ &\qquad sum((labPeriod\_to\_month(labPeriod, m)), \\ &\qquad crop\_op\_per\_till(crops, Operation, labPeriod, till)) \\ &\qquad * \ p\_EFpmfCrops(crops, operation, emissions) \\ &\qquad\qquad * \ v\_cropHa(crops, plot, till, intens, t, nCur)) \end{aligned} \tag{20}$$

4.3.2 Nitrate leaching losses

According to Lehmann and Schroth (2002, p.151) nutrient leaching is referred to "the downward movement of dissolved nutrients in the soil profile with percolating water." For N the form of the particular dissolved nutrient has a significant influence on the mobility of the nutrient in the soil. Ammonium (NH_{4+}) is generally less mobile than NO_{3-} and therefore less prone to leaching. The various forms of N in soil are transformable from one to another through the processes of nitrification and denitrification. The most common N form lost through leaching is NO_{3-} (Butterbach-Bahl et al. 2011, p.113 f.).

The amount of leached NO_{3-} is mainly determined by two factors: The N surplus in the soil and the drainage volume. The N surplus is derived from the N accumulated in the soil deducted by the N uptake of plants. The N-input into the soil can be built up from various sources, e.g. from mineral fertilizer, manure, deposition or soil organic N. Although sometimes an increase in water input may decrease NO_{3-} leaching due to increased denitrification, high leaching usually occurs when high drainage volume and high N input coincide (Di and Cameron 2002, p.239).

For the system under analysis especially leaching under grassland and arable land are of concern. Cut or mown grassland is generally less prone to nitrate leaching. As there is no cultivation in autumn mineralization of N is not as high as on arable land. Fertilization is possible during the whole growing season. Due to a steady N uptake during the vegetation period fertilization rates above 300 kg N per hectare are not necessarily leading to significant increases in NO_{3-} leaching. If grassland is grazed, leaching increases due to higher local concentrations of N in patches of urine and dung from the grazing animals. The N load under those patches can mount up to the equivalent of 1000 kg N/ha. The total leaching of the pasture is determined by the area covered with patches and hence the stocking density (Di and Cameron 2002, p.239 f.).

Arable cropping systems differ from grassland through cultivation and fallow periods. Cultivation accelerates N mineralization and fallow periods provide conditions for greater drainage. Therefore, cropped land is associated with greater N leaching losses compared to pastures. During the autumn and winter period leaching losses are usually the highest. Reasons for higher leaching are increased mineralization through higher microbial activity, higher soil moisture and post-harvest cultivation. Approximately 50-70% of the NO_{3-} in the soil is lost in autumn and winter. In some cases, the period of high leaching occurrence can be prolonged to early spring, for e.g. when the grown crops sprout late, such as maize, and therefore cannot take up the mineralized N (Di and Cameron 2002, p.240 f.). Stored manure can be a source of leaching losses, too. In Germany legal requirements for storage floor sealing prevent those kinds of losses (Rösemann et al. 2015, p.49).

To sum up, the amount of leached NO_{3-} typically varies in the following order: cut grassland < grazed pasture < arable cropping. Leaching losses are higher in autumn and winter and are increasing with greater N-input and drainage.

In FarmDyn an advanced N balance, i.e. the model Salca NO_3, is used to calculate N leaching losses based on methodology of Richner (2014). Conceptually, the underlying assumption of the model is that inputs of N from mineralization of soil-organic-N, fertilization or excretion of grazing animals is either taken up by plants or leached. The total loss of N through leaching on farm-level therefore is calculated as the sum of N inputs into the soil after gaseous N losses from fertilization $E_{NO3,Fert}$, from mineralization $E_{NO3,Mineralization}$ and from excreta of grazing animals, $E_{NO3,Grazing}$.The inputs are deducted by the amount of N taken up by plants, $E_{NO3,Uptake}$. The remaining N is then the leaching loss, $E_{NO3,Total}$:

$$\begin{aligned} &E_{\mathrm{NO3,Total}} \\ &\qquad = E_{NO3,Fert} + E_{NO3,Mineralization} + E_{\mathrm{NO3,Grazing}} - E_{\mathrm{NO3,Uptake}} \end{aligned} \tag{21}$$

The amount of leached NO_3-N from fertilization ($E_{NO3,Fert}$ in kg NO_3-N) is calculated based on the N-TAN applied to crops. The N-TAN pool from manure is calculated by multiplying the amount of applied manure *v_mandist* (m^{3}crop^{-1}) by the nutrients m^{-3}, *p_nut2inman* (kg N-TAN m^{-3}). The N-TAN pool from mineral fertilizer is calculated by the total amount of fertilizer applied, *v_syntdist* (kg) and the share of N-TAN from the total amount of fertilizer, *p_nutInSynt* (kg N (kg fertilizer)$^{-1}$). The emission factor *p_EfLeachFert* (kg NO_3-N (kg N-TAN)$^{-1}$) differentiates between crops, month and soil depth:

$$\begin{aligned} &E_{NO3,Fert} \\ &\qquad = sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens), \\ &\qquad\qquad manApplicType\_manType(ManApplicType, curManType), m) \\ &\qquad v\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m) \\ &\qquad\quad * \ sum(curManChain, p\_nut2inMan("NTAN", curManType, curManChain)) \\ &\qquad\qquad * \ p\_EfLeachFert(m, crops)) \\ &\qquad\quad + sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens), syntFertilizer, m), \\ &\qquad\quad v\_syntDist(crops, plot, till, intens, syntFertilizer, t, nCur, m) \\ &\qquad\qquad * \ p\_nutInSynt(syntFertilizer, "N") \ * \ p\_EfLeachFert(m, crops)\ ) \end{aligned} \tag{22}$$

The N leached from mineralization is based on monthly default values for mineralization that are adjusted for clay and humus content of the soil, month with heavy cultivation operations and effects of long-term organic fertilization. For permanent grassland a reduced mineralization is assumed due to a lack of cultivation operation. The default monthly N mineralization per hectare is given by the parameter *p_leachnorm*. The NO_3-N leached through mineralization, $E_{NO3,Mineralization}$ in kg NO_3-N is calculated using the exogenously determined land endowment of the farm, *p_iniLand,* in ha:

$$\begin{aligned} &E_{NO3,Mineralization} \\ &\qquad = sum(\ m, \ \ p\_LeachNorm(m) \\ &\qquad\qquad\qquad * \ sum((landtype, soil), p\_iniLand(landType, soil))) \end{aligned} \tag{23}$$

The default is then adjusted by the effects of long-term organic fertilization. The effect is estimated based on the amount of applied manure N, which is calculated by multiplying the amount of applied manure *v_mandist* (m^{3}crop^{-1}) by the nutrients per m^3, *p_nut2inman* (kg N m^{-3}). The assumption is that mineralization is increased by 10 % per 110kg N from manure per hectare as this represents the amount of excreted N per livestock unit. Note that the N pool is deducted by prior gaseous N losses, *v_emissions* in kg N:

$$\begin{aligned} * \ \ &[1 + 0.1 * \ [sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens), \\ &\qquad\qquad manApplicType\_manType(ManApplicType, curManType), m)\ , \\ &\qquad v\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m) \\ &\qquad * \ (sum(manChain, p\_nut2inMan("NORG", curManType, manChain)) \\ &\qquad + \ sum(manChain, p\_nut2inMan("NTAN", curManType, manChain))\ ) \ \ ) \\ &\qquad - \ sum(\ (curChain, NiEmissions(Emissions), m)\ , \\ &\qquad\qquad v\_emissions(curChain, "manAppl", emissions, t, nCur, m)\ ) \\ &\ ]/110/sum((landtype, soil), p\_iniLand(landType, soil))] \end{aligned} \tag{23.1}$$

The mineralization is further increased in month with heavy cultivation. The month in which heavy cultivation operations are required for the defined crops is given in *p_CFIntensTIll*, a binary parameter that indicates if in a certain month heavy cultivation operation takes place. The increase in leached N per month and hectare is given by *p_CfNLeachTill* (kg NO_3-N (ha and crop operation)$^{-1}$). The area grown per crop is given in *v_cropHa* in ha crop^{-1}:

$$+\ sum(\ (c\_s\_t\_i(curCrops(crops), plot, till, intens), m), p\_CfIntensTill(m, crops) \\ *\ p\_CfNLeachTill(m) * v\_cropHa(crops, plot, till, intens, t, nCur)\ ) \tag{23.2}$$

The reduced mineralization from permanent pastures is considered through the parameter *p_CfNLeachGrass* in kg N (ha and crop)$^{-1}$. The mineralization is deducted relative to the management intensity based on the total yield:

$$-\ sum((c\_s\_t\_i(curCrops(crops), plot, till, intens)), \\ v\_cropHa(crops, plot, till, intens, t, nCur) * p\_CfNLeachGrass(crops)\ ) \tag{23.3}$$

The absolute N pool in the soil from previous calculation steps is reduced by the amount of N taken up by plants, $E_{NO3,Uptake}$ in kg N, as can be seen in the N-mass flow depiction in Figure 5. Differing from the original approach by Richner (2014) we do not consider monthly plant uptake but a total yearly amount. The total leaching losses per year should not be biased by this, however information on the intra-yearly distribution of leaching losses is not available. The total N uptake in kg N is determined by the yield of the respective crop and is represented by the parameter *p_nutneed*:

$$E_{\mathrm{NO3,Uptake}} \\ = sum\ (\ (plot\_soil(plot, soil), c\_s\_t\_i(curCrops(crops), plot, till, intens))\ , \\ p\_nutNeed(crops, soil, till, intens, "N", t) \\ *\ v\_cropHa(crops, plot, till, intens, t, nCur)) \tag{24}$$

Due to the different conditions on grazed pastures the leaching losses, $E_{NO3,Grazing}$, from the excreta of grazing animals is calculated differently from the other fertilizer related losses. Emissions are calculated based on the monthly N excretion on pastures, *v_nut2ManurePast* in kg N, deducted by previous N emissions. A monthly specific emission factor (*p_leachPast* in kg N (kg N)$^{-1}$) takes climatic conditions into account:

$$E_{\mathrm{NO3,Grazing}} \\ = sum((c\_s\_t\_i(curCrops(crops), plot, till, intens), m), \\ (\ v\_nut2ManurePast(curCrops, plot, till, intens, "NTAN", t, nCur, m) \\ +\ v\_nut2ManurePast(crops, plot, till, intens, "NORG", t, nCur, m) \\ -\ sum((curChain, NiEmissions(Emissions))\ , \\ v\_emissions(curChain, "past", emissions, t, nCur, m)) \\ ) * p\_leachPast(m)) \tag{25}$$

4.1.1 Phosphorus losses

Phosphorus (P) losses to water bodies can lead to eutrophication which increases the growth of water weeds and algae. The decomposition of the additional organic material can absorb the oxygen from the water and can therefore substantially harm the ecosystem of a waterbody. Besides the danger for flora and fauna, algal bloom can even be harmful to humans through the release of toxins (Sharpley et al., 2001, p.287).

Agriculture, especially intensive livestock farming, is among the main emitters of P from non-point sources. The inefficient utilization of P from feedstuff for animals leads to excess P in slurry and manure, commonly applied to agricultural soils. As manure application follows the N need of the cultivated crop P is build up in the soil leading to an increased likelihood of P loss. Typical pathways of P losses are leaching, runoff and erosion (Sharpley et al., 2001, p.288). Factors influencing P losses are, inter alia, soil texture, irrigation runoff, the connectivity to stream, channel effects, and soil P status.

For the project at hand the model "SALCA Phosphor" from Prasuhn (2006) was utilized. The model comprises losses for the mentioned pathways above: erosion ($E_{P,Erosion}$), leaching ($E_{P,Leaching}$) and runoff ($E_{P,Runoff}$). The total loss of P, $E_{PO4,Total}$, is determined through the sum of the single compartments:

$$E_{\mathrm{P,Total}} = E_{\mathrm{P,Erosion}} + E_{\mathrm{P,Leaching}} + E_{\mathrm{P,Runoff}} \tag{26}$$

The underlying principle is to apply default loss factors for all pathways that are adapted to local management and pedo-climatic conditions. The advantage of the approach is the possibility to dynamically adjust the level of detail depending on the data availability.

P loss through soil erosion, $E_{P,Erosion}$ in kg P, is calculated using a default value for the eroded soil, *p_erosion in kg P ha*$^{-1}$, the share of the eroded soil that reaches water pathways, *p_lossfactor* in kg P (kg P)$^{-1}$, the P content of the eroded soil, *p_PContSoil* in kg P t^{-1}, and a factor taking into account the particle size and texture of the eroded soil P, *p_PAccuSoil*. The latter is considered, as finer particles and organic materials tend to travel further and are more likely of reaching waterbodies.

$$E_{\mathrm{P,Erosion}} = sum((c\_s\_t\_i(curCrops(crops), plot, till, intens), m), v\_cropHa(crops, plot, till, intens, t, nCur) * p\_erosion * p\_lossfactor * p\_PContSoil * p\_PAccuSoil) \tag{27}$$

P lost through leaching, $E_{P,Leaching}$ in kg P, is calculated considering soil properties, effects of fertilization with slurry, and the P content of the soil. The default values for P losses, *p_PLossLeach* in kg P ha^{-1}, are depending on the land use. For the case at hand pastures, grassland, idle land and arable land are considered. Soil properties are considered through a combined factor incorporating soil type, water capacity and depth, and grain size, *p_soilFactLeach* in kg P (kg P)$^{-1}$. The procedure of building the soil factor is described in Prasuhn (2006, p.6). P-fertilization in the form of slurry is believed to be more mobile in the soil through macro pores compared to solid manure or artificial fertilizers. Therefore, only the P input via slurry is considered. The P input through the applied slurry is given by the amount of applied slurry, v_manDist in m^3, and the P content of the slurry given by *p_nut2inMan* in kg P m^{-3}. The parameter *p_PLossFert* is the share of the applied slurry P that is lost through leaching. The P content of the top soil can lead to additional losses through leaching if the soil is over supplied with P. The factor *p_PSoilClass* is based on Walther et al. (2001):

$$\begin{aligned} E_{\mathrm{P,Leaching}} &= p\_PLossLeach(\text{"}arable\text{"}) * p\_soilFactLeach * p\_PSoilClass \\ &\quad * (1 + sum((c\_s\_t\_i(arabCrops(crops), plot, till, intens), \\ &\quad manApplicType, curMantype, m), \mathrm{p}\_PLossFert(\mathrm{low}) \\ &\quad * \mathrm{v}\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m) \\ &\quad * sum((manChain), p\_nut2inMan(\text{"}P\text{"}, curManType, manChain))) \\ &\quad /sum(soil, p\_iniLand(\text{"}arab\text{"}, soil))) * sum(soil, p\_iniLand(\text{"}arab\text{"}, soil)) \end{aligned} \tag{28}$$

The P loss through runoff, $E_{P,Runoff}$ in kg P, is calculated considering a default value, depending on the land use, a soil factor, a slope factor, a factor for the P content of the top soil and a factor considering effects of fertilization. Although the methodology allows for consideration of slope shape and the distance of waterbodies and discharges, in FarmDyn they are left out as they are believed to be plot specific and in the model such differentiation is yet not used. The default value *p_PLossRun* in kg P ha^{-1}, and the soil factor *p_soilFactRun* in kg P (kg P)$^{-1}$ comprise comparable information as the ones for P losses through leaching but with a different weighting of the single components. The slope factor *p_slopeFactor*, functions as a binary: if there is no slope (< 3%) there is no runoff at all, if there is a slope (> 3%) there are P losses through runoff. The P content of the top soil is considered in the same manner as with leaching, through the factor *p_PSoilClass*. For the effects of fertilization differing from leaching losses, besides slurry solid manure and artificial fertilizers are considered with specific loss shares, *p_PLossFert* in kg P (kg P)$^{-1}$. The P input through fertilization from organic sources is determined through the amount of applied manure *v_manDist* in m^3 and the P content *p_nut2inMan* in kg P m^{-3} of the manure. The amount of applied P from mineral fertilzers is determined through the amount of applied fertilizer *v_syntdist* in kg, and the P content of the respective fertilizer *p_nutInSynt* in kg P kg^{-1}. *p_iniLand* is the land endowment of the farm in ha:

$$\begin{aligned} E_{\mathrm{P,Runoff}} &= p\_PLossRun(\text{"}arable\text{"}) * p\_soilFactRun * p\_PSoilClass * p\_slopeFactor \\ &\quad * (1 \\ &\quad + sum((c\_s\_t\_i(arabCrops(crops), plot, till, intens), manApplicType, curMantype, m) \\ &\qquad \$(not\ sameas\ (ManApplicType, \text{"}applSolidSpread\text{"})), \\ &\quad p\_PLossFert(\text{"}high\text{"}) \\ &\quad * v\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m) \\ &\quad * sum((manChain), p\_nut2inMan(\text{"}P\text{"}, curManType, manChain))) \\ &\quad /sum(soil, p\_iniLand(\text{"}arab\text{"}, soil)) \\ &\quad + sum((c\_s\_t\_i(arabCrops(crops), plot, till, intens), manApplicType, curMantype, m) \\ &\qquad \$sameas\ (ManApplicType, \text{"}applSolidSpread\text{"}), \\ &\quad p\_PLossFert(\text{"}medium\text{"}) \\ &\quad * v\_manDist(crops, plot, till, intens, ManApplicType, curManType, t, nCur, m) \\ &\quad * sum((manChain), p\_nut2inMan(\text{"}P\text{"}, curManType, manChain))) \\ &\quad /sum(soil, p\_iniLand(\text{"}arab\text{"}, soil)) \\ &\quad + sum((c\_s\_t\_i(arabCrops(crops), plot, till, intens), syntFertilizer, m), \\ &\quad p\_PLossFert(\text{"}low\text{"}) * v\_syntDist(crops, plot, till, intens, syntFertilizer, t, nCur, m) \\ &\qquad * p\_nutInSynt(syntFertilizer, \text{"}P\text{"}))/sum(soil, p\_iniLand(\text{"}arab\text{"}, soil)) \\ &\qquad) * sum(soil, p\_iniLand(\text{"}arab\text{"}, soil)) \end{aligned} \tag{29}$$

4.1.2 Humus Balance

Soil organic matter (SOM) affects the chemical and physical properties of the soil. This includes the soil structure and porosity, the water infiltration rate and moisture holding capacity of soils, the diversity and biological activity of soil organisms, and plant nutrient availability. Through the buildup of carbon stocks, soils can even function as carbon sinks and slow down climate change (Bot & Benites 2005). Agricultural practice influences SOM in many ways: intensive production systems may drain the soils through the removal of C from the system via harvested products, the application of organic manures may increase SOM while cultivation can lead to increased mineralization and therefore losses of SOM. The interplay of the many factors affecting the SOM level makes it difficult to determine given the scarce data limitations at hand.

Humus balancing is a methodology often applied by practitioners to assess management effects on SOM. The information is mostly used as decision support for farmers and for environmental impact assessment. Although the latter is limited by the scope and therefore the precision of the tool: Most tools are designed for farmers in order to maintain SOM levels that sustain high yield levels. As a consequence, these methods, from a methodological point of view, cannot quantify SOM changes but rather assess the relative impact of different management scenarios. To counteract those shortcomings, the inclusion of side specific data, can improve the prediction accuracy (Brock 2016).

For the case at hand the balancing method from Ebertseder et al. (2014) is used. It is a commonly applied method that is even used in German legislation (Bodenschutzgesetz). The change in soil carbon, $E_{C,Change}$ in kg Humus equivalent (H_{eq})[2], is calculated through the C removal through harvest of the grown plants, $E_{C,Uptake}$ in H_{eq}, the C input from humification of incorporated crop residues $E_{C,Humification}$ in H_{eq}, the removal of C through the harvest of crop residues $E_{C,Residues}$ in H_{eq}, and the C input through organic fertilization, $E_{C,Fertilizer}$ in H_{eq}:

$$E_{C,Change} = -E_{C,Uptake} + E_{C,Humification} - E_{C,Residues} + E_{C,Fertilizer} \tag{30}$$

The C removal through harvest of the grown plants, $E_{C,Uptake}$, is calculated using the area grown with crops, *v_cropHa* in ha crop^{-1}, and a crop specific value of the C need, *p_humCrop*, in kg H_{eq} (ha and crop)$^{-1}$:

$$E_{C,Uptake} = sum((c\_s\_t\_i(curCrops(crops), plot, till, intens)), v\_cropHa(crops, plot, till, intens, t, nCur) * p\_humCrop(crops)) \tag{31}$$

The C input from humification of incorporated crop residues $E_{C,Humification}$ is calculated based on the amount of crop residues per grown crop and ha, *p_resiCrop*, in dt (crop and ha)$^{-1}$, the area of grown crops, *v_cropHa* in ha crop^{-1}, and the effect of crop residues on the soil C content, *p_resiInc* in kg H_{eq} dt^{-1}.

$$E_{C,Humification} = sum((c\_s\_t\_i(curCrops(crops), plot, till, intens)), v\_cropHa(crops, plot, till, intens, t, nCur) * sum((plot\_soil(plot, soil)), p\_resiCrop(crops, soil, till, intens, t)) * p\_resiInc(crops)) \tag{32}$$

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[2] 1 H_{eq} represents 1kg of humus C

The removal of C through the harvest of crop residues $E_{C,Residues}$ is calculated based on the area where crop residues are removed, *v_residuesRemoval in ha crop*$^{-1}$, the amount of removed residues *p_OCoeffResidues*, in t (ha and crop$^{)-1}$ and the effect of crop residues on the soil C content, *p_resiInc* in kg H$_{eq}$ dt^{-1}.

$$\begin{aligned} E_{C,Residues} \\ &= sum(\ (c\_s\_t\_i(curCrops(crops),plot,till,intens))\ \$\ cropsResidueRemo(crops), \\ &\qquad v\_residuesRemoval(crops,plot,till,intens,t,nCur) \\ &\qquad * sum(\ (plot\_soil(plot,soil),curProds), \\ &\qquad 10 * p\_OCoeffResidues(crops,soil,till,intens,curProds,t))* p\_resiInc(crops)) \end{aligned} \tag{33}$$

The C input through organic fertilization, $E_{C,Fertilizer}$ is calculated based on the amount of applied manure v_manDist in m3 and the resulting C addition to the soil C pool *p_humfact*, in kg H$_{eq}$ m^{-3}

$$\begin{aligned} E_{C,Fertilizer} \\ &= sum((c\_s\_t\_i(arabCrops(crops),plot,till,intens),manApplicType,curMantype,m), \\ &\qquad v\_manDist(crops,plot,till,intens,ManApplicType,curManType,t,nCur,m) \\ &\qquad * p\_humfact(ManApplicType)\ ) \end{aligned} \tag{34}$$

The advantage of the method is the ease of calculation due to no further data input. As mentioned earlier the advantage comes at the cost of accuracy. To partly forego this issue soil properties can be incorporated in the default values for C uptake and inputs from fertilization. Kolbe (2010) provides such values for six soil classes.

4.3.3 Emissions from off-farm inputs

Emissions that arise through the production of farm inputs can significantly influence the environmental performance of a farm. While in the national accounting of GHG emissions under the Kyoto protocol such emissions are commonly credited towards other sectors than the farming sector, in the LCA approach all emissions associated with production are considered. Following the LCA approach emissions of mayor farm inputs are calculated using the EcoInvent database (Wernet et al. 2016). The emission factors are defined and calculated using the OpenLCA[3] software. In FarmDyn emissions from Inputs (E_{input}) are calculated based on the bought inputs *v_buy and* the emission factor *p_EFInput*:

$$\begin{aligned} E_{input} \\ &= sum((inputs,sys),\ v\_buy(inputs,sys,t,nCur)\ \ *\ \ p\_EFInput(inputs,emissions)) \end{aligned} \tag{35}$$

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[3] http://www.openlca.org/

4.4 Impact assessment

The impact assessment phase of a LCA typically involves assigning the inventory data to impact categories, the modelling of the inventory data within impact categories and, in specific cases, the aggregation of results. For the impact assessment we use the ReCiPe2016 method for impact assessment at mid-point level (Huijbregts et al. 2016). The yearly aggregated emissions from the inventory analysis are related to the impact categories via characterization factors that transform the emissions into impact scores. The categorized emissions are summarized in the variable *v_emissionsCat*. The categorization is conducted using the characterization factors *p_emCat* and the yearly emissions, *v_emissionsYear*, calculated as seen above:

$$\begin{aligned}&v\_emissionsCat(curChain,source,emCat,t,ncur)\\&\quad =sum(source\_emissions(source,emissions),\\&\quad v\_emissionsYear(curChain,source,emissions,t,nCur)\ *\ p\_emCat(emCat,emissions))\end{aligned} \tag{36}$$

Considered impact categories are global warming potential, terrestrial acidification potential, marine and freshwater eutrophication potential and particulate matter formation potential.

5 Economic Indicators

Economic sustainability in the context of a farm refers to the (long term) economic viability of the farm in a changing economic context. It is commonly measured in profitability, liquidity, stability and productivity. Autonomy is a dimension that could be classified as a social indicator and/or an economic indicator. Autonomy can also be seen as an indicator for economic stability as an autonomous farm is less dependent on input prices (Latruffe et al, 2016, p.125).

5.1 Profitability

5.1.1 Contribution margin and gross profit

The contribution margin generally describes the revenue of a product deducted by its variable costs. It is a key element of break-even analysis and represents the portion of sales revenues that contributes to the coverage of fixed costs. Gross profit is equal to the contribution margin deducted by fixed costs of production. Both values are indicators for profitability of certain farm branches and are commonly used by decision makers in agriculture. Due to the complexity and size of some farms such product specific indicators help to determine the profitability of certain farm branches. Furthermore, the practice relevant indicator is easier to relate to by farmers and other stake holders in focus groups of other work packages. For the SustainBeef project the two indicators are calculated per hectare of cultivated land, per head of dairy and/or suckler cow, and per head of slaughtered heifer or bull. The calculation of the indicator is conducted post model. The different positions considered are listed in the tables 1 to 3 below:

Table 1: Contribution margin of crop production

Position	Description
Revenues	Price times yield of the harvested products; where no price is applicable the shadow price is used (forage crops)
Variable costs	
Seeds	Only for crops with yearly reseeding
Fertilizer	Mineral fertilizers for N and P
Pesticides	herbicide, insecticide, fungicide and growth control
Variable machine costs	Includes diesel and other operating costs
Water costs	For spraying pesticides, not for irrigation
Insurance	
Contribution margin	

Source: own illustration

Table 2: Contribution margin and gross product per dairy or mother cow

Position	Description
Revenues	
Milk revenue	
Old cow revenue	
Calve revenue	
Variable Costs	
Replacements	
Raising of calves	
Feed costs	
Roughages	
Concentrates	
Other costs	
Contribution margin	
Stable fix cost	
Gross product	

Source: own illustration

Table 3: Contribution margin and gross product per fattened heifer or bull

Position	Description
Revenues	
Revenues from slaughter	
Variable Costs	
Replacement	
Rearing	
Feed costs	
Roughages	
Concentrates	
Other costs	
Contribution Margin	

Source: own illustration

5.1.2 Profit/Net-present-value/ Objective value

The objective value of the optimization problem that is maximized is the averaged NPV of the farm. The NPV is the sum of discounted cash flows of an investment. It is used to determine the profitability of a projected investment. Considered cash flows are net with drawls (with drawls after taxes) from the farmer, liquidity (investments, operational cash flows and financial cash flows) and the value of leisure time/off-farm work. A short overview of the whole construct is given in Figure 6:

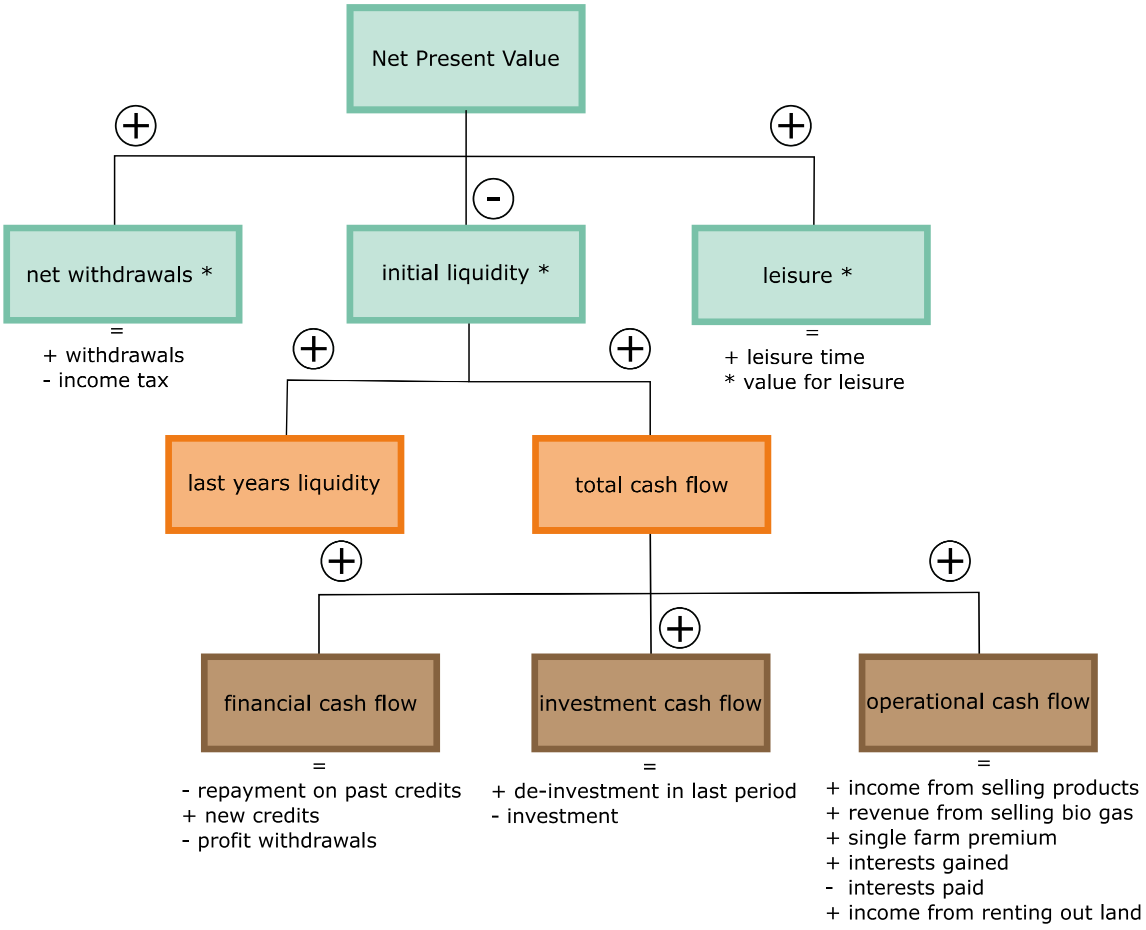

*Figure 6: Calculation of NPV. The words are marked with * if values are discounted yearly.*
Source: Own illustration

Although the NPV is often used by practitioners the comparison with the profit of actual farms yields in a significant difference. Due to the properties of the optimization model, i.e. unobserved costs not captured by the model, no stringent rational economic decision making, environmental uncertainties and other issues lead to a tendency of higher profits in the modeled farms. Nonetheless, the NPV can be used as an indicator for profitability in the comparison of different modeled scenarios. The different cash flows described above can partially be utilized as indicators on their own.

5.2 Liquidity

Liquidity refers to the availability of cash to meet immediate and short-term obligations (Latruffe et al. 2016). The indicator is highly depending on the initial endowment with capital or credits on the farm. As this kind of information is scarce and often confidential. Due to those limitations an intra-yearly depiction of the different cash flows was utilized to indicate potential shortcomings in liquidity over the year.

5.3 Stability

The economic stability is often times measured through the share and development of equity capital (Latruffe et al, 2016, p.125). Due to the data limitations on credits and debts on farms as described under liquidity, the indicator proposed under liquidity and stability are reported as one indicator.

5.4 Productivity

According to Latruffe et al. (2016) "Productivity is a measure of the ability of the factors of production to generate output." For the case at hand the factor productivity for capital, land and working hours are calculated. The ratios are calculated for different output units, those are per kg protein output, per kg calorie output and per kg beef produced. The calculation of the different indicators is depicted in the tables 4-6 below:

5.4.1 Productivity of invested capital

Table 4: Indicators and the respective unit used for the calculation of the capital productivity.

Capital	**Output**
Assets (Land, Buildings, infrastructure, Machinery)	Per kg of calorie output
Value of Inputs (Energy, fertilizer, pesticides, work)	Per kg of protein output
	Per kg of beef output

Source: own illustration

5.4.2 Land productivity

Table 5: Indicators and the respective unit used for the calculation of the land productivity.

Land	**Output**
Arable land	Per kg of calorie output
Grassland	Per kg of protein output
Pastures	Per kg of beef output

Source: own illustration

5.4.3 Productivity of work

Table 6: Indicators and the respective unit used for the calculation of the work productivity.

Work hours	**Output**
Management work (whole farm)	Per kg of calorie output
Management work (branch specific)	Per kg of protein output
Field work	Per kg of beef output
Animal related work	

Source: own illustration

5.5 Autonomy

Autonomy refers to the freedom or dependencies of the farm. Due to aforementioned problems of data limitations on some dependencies (credits, payables, liabilities etc.) the degree of autonomy of the farm is modeled using two indicators: the share of subsidies and premiums on profit and the ratio of external inputs and profits.

5.5.1 Share of subsidies and premiums on profit

The share of subsidies and premiums on profit indicates if the farm is dependent on political aid. If a farm is highly dependent on such payments, a change in the political agenda can pose a serious threat to the farms long term sustainability. Included subsidies under the CAP are direct payments (cross compliance, Greening), coupled payments per head of cattle, payments for agri-environmental schemes and organic farming. The profit is measured as NPV. Further information on the NPV can be found in Chapter 5.1.2.

5.5.2 Ratio of external inputs (feeds, fertilizers etc.) and contribution margin

Comparable to the dependence on subsidies the dependence on external inputs can threaten the long-term economic sustainability of an enterprise if for example input prices change. Therefore, systems that are less sensitive to input availability and input price fluctuations are believed to be more sustainable.

6 Social Indicators

The social dimension of sustainability can be differentiated into two categories depending on the scope of analysis: at the farm community stage and at a societal stage. The farm community refers to the farmer and his/her family, indicators therefore try to assess the wellbeing of the farm community (quality of life, physical and psychological well-being). At the societal level "external social objectives are related to society's demands, depending on its values and concerns" (Lebacq et al., 2013, p.315). Indicators aiming at the societal level of social sustainability can be further categorized into three groups: multi-functionality, acceptable agricultural practice and quality of products. As most of such indicators are of qualitative nature or extent the scope and capabilities of the modeling approach, here the focus was set on quantitative indicators aiming at the farm community, i.e. work-related indicators. Nonetheless, the social sustainability is closely linked to the other dimensions, for example a high economic profitability and stability is clearly related to the well-being of the farm community and a natural environment is among the societal demands towards agriculture.

6.1 Work-time related indicators

The depiction of work in FarmDyn differentiates work by farm branch and type of work. Figure 7 depicts the distribution of work and the differentiation of work:

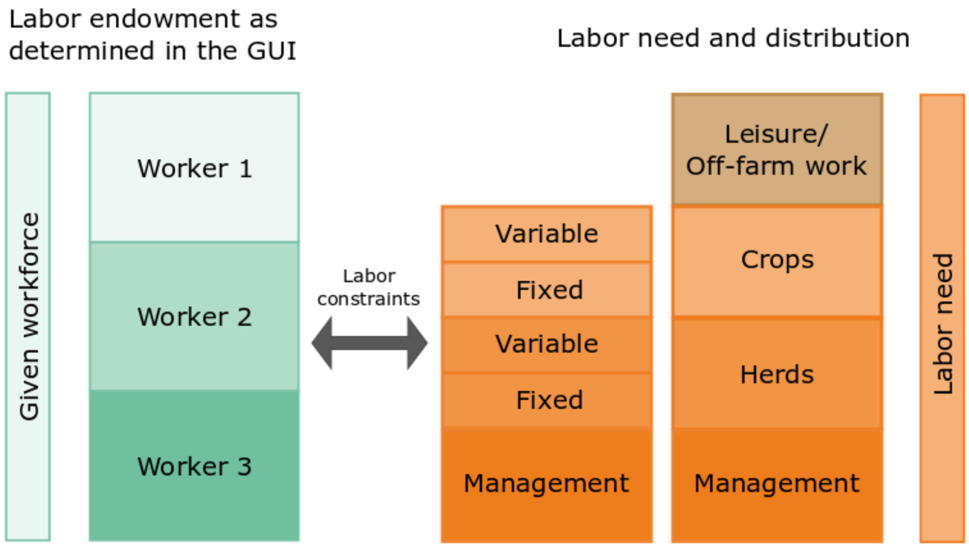

Figure 7: Labor requirements and Labor needs. Source: Own illustration
Source: Own illustration

Two types of work are considered: management activities and labor needs for farm operations. The management work is further divided into branch specific and general management work. The branch specific management work consists of a fixed amount not depending on the branch size and a linear term depending on the branch size. Farm operations are for example fertilizing or ploughing. The time requirements of these operations are linked to the mechanization level. The resulting total labor need has to be fulfilled by the given workforce. Further constraints limit the monthly and daily maximum working time and available field working days over the year.

6.1.1 Total workload and distribution over the year

The total work load can indicate the contribution of the farm to employment. The distribution of work over the year helps to identify work peaks. Work peaks mean a heavy workload, a more even distribution of work over the year is therefore desirable.

6.1.2 Work distribution by type of work

The type of work can indicate potential hazards resulting from work conditions. For example, management work is perceived as less harmful than (harder) field work/ spraying pesticides. Still this indicator has to be interpreted with caution as the perception of work is highly subjective and compared to reality, the FarmDyn work still is highly generalized/aggregated.

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Annex I Sets and set-elements

Set	Set Elements	description
arabCrops	WinterWheat, WinterBarley, SummerCere, WinterRape,…	Crops that are only to be grown on arable land
breeds		Current breeds in the model
crops	WinterWheat, WinterBarley, SummerCere, WinterRape,…	All available crops
crop_op_per_till		Crop operations per labourperiod
cropsResidueRemo	WinterWheat, WinterBarley, SummerCere…	Crops which allow residue removal
c_s_t_i(past,plot,till,intens)	Cross set	Allowed combination of crops, plots, tillage types and intensity levels
dcows	Specified by user	Dairy cow types as specified by the user
emCat	GWP, PMFP, TAP, FEP, MEP	Emission categories after characterization
emissions	N2O, NH3, NOx, N2, N2Oind, NO3, NSoilSurplus, PsoilSurplus, CH4, CO2, TSP, PM25, PM10	All emissions considered
feedAttr	DM, XF, aNDF, XP, nXP, RNB, NEL, ME, XS+XZ , XL, P , energ, crudeP , Lysin, phosphFeed, kalium, mass, ADF, UDP, GE, bSX, Ca, Mg, Na, K, RNBmin, RNBmax, DMR, DMRMX, DMMX, NFE	Attributes of feedstuff, GE is gross energy, DM is dry matter…
feedregime	normFeed, fullGraz, partGraz, noGraz	Different feed regimes, amount of grazing in the diet
feeds	earlyGraz, middleGraz, lateGraz, earlyGrasSil, middleGrasSil, lateGrasSil, hay, MaizSil, Summerpeas, Summerbeans, ConcCattle1, milkPowder, OilsForFeed, SoyBeanMeal, straw, milkFed	Feedstuff for feeding
herds	mCalvsRais, fCalvsRais, pigletsBought, cows, heifsSold, bullsSold, heifsBought, remonte,…	Different herds by animal categories
inputs		All farm inputs in the model
intens	hay, bales, silo, graz, normal, fert80p, fert60p, fert40p, fert20p	Intensity levels and harvest type for grassland

Set	Set Elements	description
labperiod		Two-weekly labour periods
labPeriod_to_month		Mapping of baourperiods to month
m		month
manApplicType	applSpreadCattle, applTailhCattle, applInjecCattle, applTShoeCattle, applSolidSpread, applSpreadLightCattle, applTailhLightCattle, applInjecLightCattle, applTShoeLightCattle	Manure application techniques by manure type
manApplicType_manType		Allowed combinations of manure types and application techniques
manChain; alias (curChain, curManchain, chain)	LiquidPig, LiquidCattle, LightLiquidCattle, SolidCattle, LiquidBiogas, LiquidImport	Manure management system
manStorage	Storsub, stornocov, storstraw, storfoil	Manure storage type/ cover type
manType	cowsMin, MCMin, heifsMin, fcalvsRaisMin, mcalvsRaisMin, bullsMin, cowsMax, MCMax, heifsMax, fcalvsRaisMax, mcalvsRaisMax, bullsMax,…	Different manure types by animal category, min/max values are determined by N:P values
n		Decision nodes in tree
NiEmissions		Nitrogen related emissions
nut2	Norg, NTan, P	Plant nutrients considered
operation	Herb, sowMachine, directSowMachine, seedBedCombi, springTineHarrow, rotaryHarrow, mulcher, singleSeeder,…	Field operations
past		Subset of crops, grazed grassland types
plot	Plot1-plot9	Available plots
plot_soil		Allowed combination of soil types and plots
prods		All products produced at farm
prodsResidues		Products from crop residues
resiEle	duration, freqHarv, DMyield, DMresi, aboveRat, aboveN, belowRat, belowN	Elements for calculation of emissions from crop residues

Set	Set Elements	description
Soil	l, m, h	Soil types (light, medium, heavy)
source	past, entFerm, staSto, manAppl, minAppl, field, input, process	Emission sources
stableStyles	Slatted_floor, Cubicle_House, Tie_Stall, Shed, Deep_Litter	Different stable types
syntfertilizer	ASS, AHL, KAS, PK_18_10, KaliMag, Lime	Synthetic fertilizer types
sys	eco, conv	Distinction between organical and convential farming
t		Simulation years
till	hay, plough, minTill, noTill , eco, bales, silo, graz	Tillage types

Annex II Parameters and parameter values

Gaseous emissions

Parameter	Description	Value	Source
p_Ym	Methane conversion factor in %	dcows 6.32 Heifs 6.5 calvs 4.1 bulls 3 mcows 6.5	Haenel et al. (2018) p. 140 Table 4.22, p.145, p. 155, p.168, p.214, p.194
p_BO	Maximum methane producing capacity in m^3 CH$_4$ (kg volatile solid)$^{-1}$	LiquidCattle 0.23 LightLiquidCattle 0 SolidCattle 0.23	Haenel et al. (2018) p.108 and p. 185
p_MCF	Methane conversion factors for each manure management system in %	For system without cover: LiquidCattle 1 LightLiquidCattle 0 SolidCattle 17 Other systems: LiquidCattle 17 LightLiquidCattle 0 SolidCattle 17	Haenel et al. (2018) p.108 and p. 185
p_densM	denisty of methane in kg m^{-3}	0.67	Dong et al. (2006) p.10.41
p_MCFPast	Methane conversion factors for excreta on pastures in %	1	Haenel et al. (2018), p. 108
p_EFSta	Cattle, partial emission factor for NH$_3$-N from housing (related to TAN) in kg NH$_3$-N (kg N)$^{-1}$	0.197	Haenel et al. (2018), p. 108
p_EFSto	Cattle, partial emission factor for NH$_3$-N from storage (related to TAN) in kg NH$_3$-N (kg N)$^{-1}$	0.15	Haenel et al. (2018), p. 109
p_EFStaSto (N_2O)	Cattle, partial emission factors for direct N_2O-N from housing and storage applied to total N in system in kg N_2O-N (kg N)$^{-1}$	LiquidCattle 0.005 LightLiquidCattle 0.005 SolidCattle 0.01	Haenel et al. (2018), p. 110

Parameter	Description	Value		Source
p_EFStaSto(NO_X)	Cattle, partial emission factors for direct NO_X-N from housing and storage applied to total N in system in kg NO_X-N (kg N)$^{-1}$	LiquidCattle LightLiquidCattle SolidCattle	0.0005 0.0005 0.001	Haenel et al. (2018), p. 54
p_EFStaSto(N_2)	Cattle, partial emission factors for direct N_2 from housing and storage applied to total N in system in kg N (kg N)$^{-1}$	LiquidCattle LightLiquidCattle SolidCattle	0.015 0.015 0.03	Haenel et al. (2018), p. 54
p_EFpasture(NH_3)	Dairy cows, partial emission factors for NH_3-N from pastures (related to TAN excreted) in kg NH_3-N (kg N)$^{-1}$	0.1		Haenel et al. (2018) p.137
p_EFpasture(N_2O)	Dairy cows, partial emission factors for N_2O-N from pastures (related to TAN excreted) in kg N_2O-N (kg N)$^{-1}$	0.02		Haenel et al. (2018) p. 332
p_EFpasture(NO_X)	Dairy cows, partial emission factors for NO_X-N from pastures (related to TAN excreted) in kg NO_X-N (kg N)$^{-1}$	0.012		Haenel et al. (2018) p.332
p_EFpasture(N_2)	Dairy cows, partial emission factors for N_2 from pastures (related to TAN excreted) in kg N (kg N)$^{-1}$	0.14		Rösemann et al. (2015), p.324

Parameter	Description	Value	Source
p_EFapplMan	Cattle, NH_3-N emission factors for application of slurry and digested manure (related to TAN) in kg NH_3-N (kg N)$^{-1}$	Slurry on grassland: applSpreadCattle 0.6 applTailhCattle 0.54 applInjecCattle 0.24 applTShoeCattle 0.36 Slurry on arable land with incorporation: applSpreadCattle 0.4 applTailhCattle 0.24 applInjecCattle 0.24 applTShoeCattle 0.36 Slurry on arable land without incorporation: applSpreadCattle 0.5 applTailhCattle 0.46 Solid manure: Grassland 0.9 Arable land 0.9 Sewage on grassland: applSpreadLightCattle 0.2 applTailhLightCattle 0.14 applInjecLightCattle 0.04 applTShoeLightCattle 0.08 Sewage on arable land: applSpreadLightCattle 0.2 applTailhLightCattle 0.18 applInjecLightCattle 0.04 applTShoeLightCattle 0.08	Haenel et al. (2018), p. 111 f.

Parameter	Description	Value		Source
p_EFApplMinNH3	NH_3-N emission factors for the fertilizer categories applied in Germany in kg NH_3-N (kg N)$^{-1}$	ASS AHL	0.007 0.081	Haenel et al. (2018) p.325
p_EFApplMin(N_2O)	Emission factor for emissions of N_2O-N due to mineral fertilizer application in kg N_2O-N (kg N)$^{-1}$	0.01		Haenel et al. (2018) p.326
p_EFApplMin(NO_X)	Emission factor for emissions of NO_X-N due to mineral fertilizer application in kg NO_X-N (kg N)$^{-1}$	0.012		Haenel et al. (2018) p.326
p_EFApplMin(N_2)	Emission factor for emissions of N_2 due to mineral fertilizer application in kg N (kg N)$^{-1}$	0.07		Roesemann et al. 2015, pp. 316-317
p_EFN2Oind	Emission factor of indirect N_2O-N due to deposition in kg N_2O-N (kg N)$^{-1}$	0.01		Klein (2006) Table 11.24
p_EFN2OindLeach	Emission factor of indirect N_2O-N due to leaching in kg N_2O-N (kg N)$^{-1}$	0.0075		Klein (2006) Table 11.24
p_EFlime	Emission factor of CO_2 emissions due to liming In kg CO_2 (t lime)	1714.286		Klein (2006) p.11.27
p_EFInput	Emission factor for several emissions due to production of farm inputs	Confidential		EcoInvent

Phosphorus loss accounting

Parameter	Description	Value		Source
p_erosion	Average soil lost through erosion in t ha^{-1}	3		
p_lossfactor	Share of eroded soil reaching surface waters in t t^{-1}	0.2		Prasuhn (2006) p.2
p_PContSoil	P content of the eroded soil in kg P t^{-1}	0.95		Prasuhn (2006) p.3
p_PAccuSoil	P accumulation in eroded soil in finer particles	1.86		Prasuhn (2006) p.3
p_PLossLeach	Average amount of P lost through leaching in kg P ha^{-1}	grass	0.06	Prasuhn (2006) p.5
		arable	0.07	
		idle	0.05	
		idleGras	0.05	
p_soilFactleach	Correction factor for influence of soil properties on P losses from leaching	1 (default)		Prasuhn (2006) p.5f.
p_PSoilClass	Correction factor for P content of soil	1 (default)		Prasuhn (2006) p.7
p_PLossFert	Correction factor for type and amount of fertilizer	low	(1.2-1)/80	Prasuhn (2006) p.7 and p. 13
		medium	(1.4-1)/80	
		high"	(1.7-1)/80	
p_PLossRun	Average amount of P lost through run off in kg P ha^{-1}	grass	0.25	Prasuhn (2006) p.9
		arable	0.175	
		idle	0.1	
		idleGras	0.1	
p_soilFactRun	Correction factor for influence of soil properties on P losses from run off	1 (default)		Prasuhn (2006) p.10f.
p_slopeFactor	Binary trigger for slope of field	“1” if slope is > 3% “0“ if slope is < 3%		Prasuhn (2006) p.10

Nitrate leaching accounting

Parameter	Description	Value		Source
p_EfLeachFert	Monthly leaching potential of N fertilization, related to N-TAN in kg N (kg N-TAN)$^{-1}$	WinterWheat		Richner (2014) p.20
		JAN	0.5	
		FEB	0.3	
		MAR	0.1	
		APR	0	
		MAY	0	
		JUN	0	
		JUL	1	
		AUG	1	
		SEP	1	
		OCT	1	
		NOV	1	
		DEC	1	
		SummerCere		
		JAN	1	
		FEB	0.5	
		MAR	0.3	
		APR	0.1	
		MAY	0	
		JUN	0	
		JUL	0	
		AUG	1	
		SEP	1	
		OCT	1	
		NOV	1	
		DEC	1	
		WinterRape		
		JAN	0.2	
		FEB	0.1	
		MAR	0	
		APR	0	
		MAY	0	
		JUN	0	
		JUL	1	
		AUG	0.8	
		SEP	0	
		OCT	0	
		NOV	0.2	
		DEC	0.2	
		…		

Parameter	Description	Value		Source
p_LeachNorm	Default mineralization in kg N ha^{-1}	Default for valley/plain fields		Richner (2014) A12
		JAN	0	
		FEB	0	
		MAR	5.8	
		APR	9.1	
		MAY	11.6	
		JUN	14.9	
		JUL	17.4	
		AUG	20.7	
		SEP	23.2	
		OCT	11.6	
		NOV	5.8	
		DEC	0	
p_CfIntensTill	Binary trigger for heavy cultivation operation for certain crops in certain month	WinterWheat		Richner (2014) p.13 (for classification of operation, actual operations are exogenous factors in the cropping module)
		JAN	0	
		FEB	0	
		MAR	0	
		APR	0	
		MAY	0	
		JUN	0	
		JUL	0	
		AUG	0	
		SEP	1	
		OCT	1	
		NOV	0	
		DEC	0	
		Summercere		
		JAN	0	
		FEB	0	
		MAR	1	
		APR	0	
		MAY	0	
		JUN	0	
		JUL	0	
		AUG	0	
		SEP	0	
		OCT	1	
		NOV	0	
		DEC	0	
		…		

Parameter	Description	Value		Source
p_CfNLeachTill	Extra N mineralization from month with intense cultivation in kg N ha^{-1}	Default for valley/plain:		Richner (2014) p.12
		JAN	0	
		FEB	0	
		MAR	4	
		APR	6	
		MAY	8	
		JUN	10	
		JUL	12	
		AUG	17	
		SEP	15	
		OCT	8	
		NOV	4	
		DEC	0	
p_CfNLeachGrass	Factor to account for reduced N mineralization on grassland depending on the yield level in kg N (ha and month)$^{-1}$	Yield	Reduction of mineralization	Richner (2014) p.15
		<6t DM ha^{-1}	2.24	
		>6t DM ha^{-1}	1.72	
		>10t DM ha^{-1}	1.2	
p_leachPast	Monthly N leaching from excreta of grazing animals in kg N (livestock unit)$^{-1}$	JAN	0.078	Richner (2014) p.25
		FEB	0.069	
		MAR	0.069	
		APR	0.051	
		MAY	0.051	
		JUN	0.051	
		JUL	0.051	
		AUG	0.051	
		SEP	0.051	
		OCT	0.069	
		NOV	0.078	
		DEC	0.078	

Humus balance

Parameter	Description	Value		Source
p_humCrop	Humus depletion through crop cultivation in H_{eq} (crop and ha)$^{-1}$	WinterWheat	400	Ebertseder et al. (2014), Excel-tool LFL
		SummerCere	400	
		WinterRape	400	
		MaizSil	800	
		WinterBarley	400	
		Potatoes	1000	
		Sugarbeet	1300	
		MaizCorn	800	
		MaizCCM	800	
		Summerpeas	-160	
		Summerbeans	-160	
		WheatGPS	400	
		Idle	-180	
		catchCrop	-100	
p_resiInc	Effect of crop residue incorporation on soil carbon content in H_{eq} dt^{-1}	WinterWheat	7	Ebertseder et al. (2014), Excel-tool LFL
		SummerCere	7	
		WinterRape	7	
		WinterBarley	7	
		Sugarbeet	1.3	
		MaizCorn	7	
		MaizCCM	7	
p_humfact	Effect of organic fertilizers on soil carbon content in H_{eq} m^{-3}	applSpreadCattle	11	Ebertseder et al. (2014), Excel-tool LFL
		applTailhCattle	11	
		applInjecCattle	11	
		applTShoeCattle	11	
		applSolidSpread	34	

Particulate matter formation

Parameter	Description	Value	Source
p_EFpmfHerds	Emission factors for particle emissions from animal housing in kg place^{-1}	No grazing, TSP: dcows,straw 0.94 dcows,slurry 1.81 calvs,straw 0.35 heifs,straw 0.52 heifs,slurry 0.69 bulls,straw 0.52 bulls,slurry 0.69 mcows,straw 0.52 mcows,slurry 0.69 No grazing, Pm10: dcows,straw 0.43 dcows,slurry 0.83 calvs,straw 0.16 heifs,straw 0.24 heifs,slurry 0.32 bulls,straw 0.24 bulls,slurry 0.32 mcows,straw 0.24 mcows,slurry 0.32 No grazing, Pm2.5: dcows,straw 0.28 dcows,slurry 0.54 calvs,straw 0.1 heifs,straw 0.16 heifs,slurry 0.21 bulls,straw 0.16 bulls,slurry 0.21 mcows,straw 0.16 mcows,slurry 0.21 For part-time grazing the emission factor is multiplied by 0.5 under the assumption that the animals are kept on pastures for half of the time	Haenel et al. (2018) p.139,157,165,170,175

Parameter	**Description**	**Value**	**Source**
p_EFpmfCrops	Emission factors for particle emissions from crop operations in kg $crop^{-1}$ ha^{-1}	Cultivation operation: Pm10 0.25 Pm2.5 0.015 Harvest operation, Pm10: WinterWheat 0.49 WinterBarley 0.41 Hay 0.25 Harvest operation, Pm2.5: WinterWheat 0.02 WinterBarley 0.016 Hay 0.01 Drying operation, Pm10: WinterWheat 0.19+0.56 WinterBarley 0.16+0.43 Drying operation, Pm2.5: WinterWheat 0.009+0.168 WinterBarley 0.008+0.129	EMEP (2016) 3.D p.20

Characterization factors

		Globalwarming potential	**Particulate matter formation potential**	**Terrestrial acidification potential**	**Freshwater eutrophication potential**	**Marine water eutrophication potential**
Emission	*Unit*	kg CO_2-eq kg^{-1}	kg $Pm_{2.5}$-eq. kg^{-1}	kg SO_2-eq kg^{-1}	kg P-eq. kg^{-1}	kg N-eq. kg^{-1}
CH_4	kg CH_4	34				
CO_2	kg CO_2	1				
N_2O	kg N_2O	298				
NH_3	kg NH_3		0.24	1.96		0.1
NO_X	kg NO_X		0.11	0.36		0.04
NO_3	Kg NO_3		0.39			0.03
$Pm_{2.5}$	kg $Pm_{2.5}$		1			
P	Kg P				1	