D3.3: Report on the feasibility to integrate new functional relationships in accounting tools and national inventories

WP3: Component modelling

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1 Introduction

At the heart of international agreements on atmospheric pollution is a recognition that such pollution does not respect international geographic boundaries and that every country has an obligation to reduce the impact of their emissions on their neighbours. Emission inventories are fundamental to achieving international agreement that countries are fulfilling this obligation. They do this by performing two main functions:

- Provide the basis for assessing the impact of a country's atmospheric pollution on the human population and the natural environment of other countries, in the past, present and future.
- Provide mutual assurance that international commitments to reduce emissions are being met.

For emissions of greenhouse gases, the impact of emissions is global and hence agreements to reduce emissions are global (UNFCCC[1]). For emissions of other compounds that either indirectly impact global warming (e.g. black carbon) or have impacts that are spatially variable (e.g. ammonia), the agreements may be regional (e.g. CLRTAP[2]).

In addition to directly performing their international function, a country's emission inventory can provide information that is useful internally. For example, it enables key sources to be identified, so mitigation/abatement measures can be targeted, and inform the debate about the impact of a country's atmospheric pollution on the human population and the natural environment within its own national boundaries. To fulfil their objectives both internationally and nationally, inventories must meet five quality criteria: transparency, consistency, comparability, completeness and accuracy. However, these criteria are difficult to define concisely and can require compromises between criteria.

The most common challenges are transparency, completeness and accuracy. Accurate reporting of emissions will often require using a detailed emission inventory methodology, which unless carefully reported, can reduce transparency. Conversely, the requirement for completeness may necessitate including emissions from sources that theoretically make a significant contribution but for which there are few data on which to base emission estimates. The balance between the different quality criteria also varies between compounds. When a new compound needs to be included in inventory (which is only relevant to CLRTP), the methodology may be relatively simple, reflecting the lack of empirical data to support more detailed methodologies. As time progresses, and especially if the political focus on a compound increases, there is a need to increase the level of detail in the methodology.

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[1] United Nations Framework Convention on Climate Change

[2] UNECE's Convention on Long-range Transboundary Air Pollution

The latter case is currently true for greenhouse gas (GHG) and ammonia (NH_3) emissions from agriculture. Most countries have made commitments to national reductions in GHG as part of the Paris Agreement. For European countries, this is also true for NH_3 emissions, as part of either the EU NECD[3] or CLRTAP. The reductions in GHG emissions are both large and urgent, and the evidence linking particulate pollution and human health is likely to increase pressure for further reductions in NH_3 emissions. Agriculture is a significant source of GHG emissions and already accounts for 92% of European NH_3 emissions. Unless GHG mitigation measures are implemented, agriculture is projected to be the largest single source in the EU in 2050. As a consequence, we can expect an increased focus on emission inventories and especially on mitigation measures, their cost effectiveness, and how their implementation should be reflected in national emission inventories.

In this document, we consider the processes driving emissions of GHG and NH_3, how these are reflected in the IPCC guidelines and UNECE guidebook, and how emission factors and functional relationships drawn in MELS T3.1 could potentially be included in national inventories, in the light of how the increasing importance of these emissions in the political arena is likely to change the guidance needed by inventory compilers. The MELS project considered emissions of NH_3, N_2O and CH_4 from manure in livestock housing and manure storage. The emissions of these gases from field-applied manure were part of a companion project (DATAMAN)[4].

2 Overview of processes

The losses of greenhouse gases from manure management depend on a mixture of management and environmental factors. The main gaseous emissions from manure management are:

- Direct nitrous oxide (N_2O)
- Methane (CH_4)
- Indirect N_2O emissions as a consequence of ammonia (NH_3) emissions.
- Indirect N_2O emissions as a consequence of nitrate leaching and runoff from manure storage.
- Carbon dioxide (CO_2), but only in connection with C sequestration

The production of N_2O and CH_4 from manure in either indoor or outdoor storage is dependent on biological processes, which in turn depend on the quantity and quality of C and N in the manure, the presence of the relevant micro-organisms, the availability of oxygen and the temperature. The availability of oxygen and the temperature are themselves dependent on the type of manure (liquid or solid) and the physical structure of the storage. The production of both gases is also sensitive to pH. However, since the responsible micro-organisms have some ability to adapt to their physical and chemical environment, this

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[3] National Emission reduction Commitments Directive

[4] https://www.dataman.co.nz/

sensitivity is mainly relevant when pH is substantially reduced, as when slurry is acidified. Since both N_2O and CH_4 are relatively insoluble in water, these gases are expelled from the manure into the atmosphere.

Similar factors affect the emission of CH_4 and N_2O in the soil as in the manure storage, although the details of the mechanisms can differ substantially. Soils are not considered large source of CH_4 (wetlands excepted), with relatively low emissions arising from excreta deposited on pasture by grazing livestock. Emissions may occur from soil in holding areas for livestock (e.g. corrals) but such places are more appropriately considered as livestock housing without walls, not fields. When manure N is applied to the soil, once the initial loss of N as NH_3 has occurred, both the mineral and organic N enter the corresponding N pools in the soil. Emissions of N_2O can be associated with both the processes of nitrification and denitrification. Distinguishing the N_2O emissions associated with manure N from those associated with other N sources is therefore difficult, unless they can be linked to localized concentrations of manure N, such as occurs in lumps of solid manure or in the furrows created during slurry injection.

For NH_3, the situation is somewhat different, since the processes involved are mainly chemical and physical, not biological, and NH_3 is highly soluble in water. Most of the N that is vulnerable to emission is excreted by livestock in urine, in the form of urea and other low-molecular weight compounds. These compounds rapidly decompose to form a mixture of ammonia and ammonium in solution (together called Total Ammoniacal Nitrogen or TAN). Poultry are an exception, since the N is mainly excreted as uric acid. All these compounds are normally mineralised shortly after excretion, either by micro-organisms or by the enzymes excreted by them. This results in a pool of ammonium that is the source of the NH_3. The ammonium in the liquid phase of the manure is in dynamic equilibrium with NH_3 in solution, with the equilibrium favouring NH_3 in the pH range common in manure (>7). At the wet surface of the manure, the NH_3 in solution is in dynamic equilibrium with NH_3 in the air immediately above that surface. The concentration of NH_3 in the air at the wet surface is much higher than that in the free atmosphere, so the processes of molecular and/or turbulent diffusion transport NH_3 away from the manure towards the free atmosphere. Relative to the free atmosphere, the volatilisation of NH_3 can therefore be viewed as a ‘pull’ process, in contrast to the ‘push’ process for CH_4, CO_2 and N_2O. This difference between NH_3 volatilisation and the emission of CH_4, CO_2 and N_2O means that instantaneous NH_3 emissions are determined by the surface area of manure exposed to the atmosphere and not to the volume of manure. However, for manure in storage, the volume does influence the cumulative NH_3 emission, since it affects the extent to which the depletion of TAN near the manure surface is counteracted by the transport to the surface from within the mass of manure. For field-applied manure, the situation is further complicated by the presence of mechanisms that remove TAN from solution or increase the resistance to the transport of NH_3 to the free atmosphere. For all manure types, factors such as infiltration, rainfall, irrigation, incorporation that lead to the liquid phase of the manure entering the soil matrix, will reduce NH_3 emission. This is partly because the resistance to NH_3 transport in the soil is much greater than in the atmosphere and partly because ammonium is removed from solution by becoming bound to the soil CEC.

Since manure storage is normally an anaerobic environment, the majority of manure N is present as ammonium (TAN) or organic N, rarely as nitrate. As a result, the loss of manure N via nitrate leaching normally occurs after it has undergone one or more transformations. If manure is applied immediately prior to a period when effective rainfall is high, crop uptake is low or zero (either because of low air temperature or because no crop is present) and soil temperature is well above zero, the manure organic N can be mineralised to TAN, the TAN can be nitrified and then the nitrate lost via leaching. This situation commonly occurs in the autumn in temperate regions of the world and possibly in high-rainfall areas elsewhere, in the period between crops. However, if manure N is applied just prior or during the growing season, much of the TAN applied will be absorbed by the crop, together with additional TAN created by the mineralisation of manure organic N. Some of the manure N taken up by the crop will remain in the soil after harvesting as crop residues, and the mineralisation of these residues, together with that of the remaining manure organic N, can fuel nitrate leaching in the autumn and winter. Note that crop residues also arise as a consequence of alternative sources such as fertiliser and N fixation, and these too can contribute to nitrate leaching.

2.1 Functional relationships

Within the context of emission inventories, functional relationships are essentially simple models. The usual approach to the construction of emission inventories involves the multiplication of an activity (e.g. number of cows) and an emission factor (e.g. emission per cow). This is a linear model but functional relationships do not necessarily need to be linear.

The levels of detail in functional relationships map onto the Tier level categorization of IPCC and UNECE, and the level of detail increases from Tier 1 to Tier 3. In IPCC and UNECE, Tier 2 should always be used for key sources and Tier 1 is only permitted for sources that are not. Tier 3 means any methodology that is greater than Tier 2. This means that there is potentially a wide range of detail in methodologies that would fall within the definition of Tier 3. Here we distinguish this level of detail by an additional letter e.g. Tier 3a for a methodology that is only slightly more detailed than Tier 2 (sometimes called Tier 2+), Tier 3b for more detailed methodologies, etc.

Both IPCC and UNECE have developed Tier 1 methodologies that calculate emissions as the number of livestock in a category multiplied by an undifferentiated emission factor for the category (Table 1).

Table 1: Structure of the IPCC (2019) and UNECE (2016) methodologies relating to CH_4, N_2O and NH_3.

	IPCC (2019)			UNECE (2019)
Tier level	CH_4	N_2O	NH_3	NH_3
	Livestock housing & manure storage			
1	Simple national livestock excretion, storage type, climate zone, default emission factors	Simple national livestock excretion, storage type, default emission factors		Livestock category, solid v liquid manure, default emission factors
	Manure application			
	NA	Total N in manure, default emission factors		Livestock category, solid v liquid manure, default emission factors
	Deposition to pasture			
	Simple livestock excretion, default emission factors	Total N in manure, default emission factors		Livestock category, default emission factors
2	Livestock housing			
	NA (combined estimation with storage)	NA (combined estimation with storage)	NA (combined estimation with storage)	N excretion by livestock category and performance, solid v liquid manure, TAN[1] and organic N, default emission factors
	Manure storage			
	Complex national livestock volatile solids (VS) excretion, storage type, climate zone, national emission factors	Complex national livestock N excretion, storage type, national emission factors		Solid v liquid manure, TAN and organic N flow, default emission factors
	Holding yard			
	Complex national livestock VS excretion, climate zone, national emission factors[2]	Complex national livestock N excretion, storage type, national emission factors		Solid v liquid manure, TAN and organic N flow, default emission factors
	Manure application			
	NA	Total N in manure[3], climate zone, national emission factors		Solid v liquid manure, TAN and organic N flow, default emission factors
	Deposition to pasture			
	Complex national livestock VS and N excretion, national emission factors			TAN, default emission factors

[1] Interpreting dry lot to equate to holding yard

[2] TAN = total ammoniacal nitrogen

[3] Recommendation to use N flow approach to account for N losses in manure management

Ideally, emission inventories would be constructed using methods that captured the effect of the major structural, management and environmental factors on emissions and that used readily available, high quality input data. These methods would be constructed using a knowledge of the processes underlying the emissions, combined with high quality, empirical data from well-balanced experiments that cover the full extent of the management and environmental conditions under which the method would be used. In practice, there are major constraints on achieving this ideal situation:

1. Our knowledge is incomplete
2. The empirical datasets are generally not comprehensive and always unbalanced
3. The activity data or parameter values are not readily available.

The choice of the most appropriate model to use as part of a methodology will vary between contexts and locations. A model to be used for reporting emissions in emission inventories needs to support good inventory practice. This means that the model must be supported by empirical data, use good quality input data and parameters and be transparent. This implies that the models tend to err towards simplicity, including only the major driving variables, rather than all the variables our knowledge would suggest can affect emissions, and using parameters that are estimated statistically using empirical data. In addition, empirical models capture in their error terms all the real-world effects not explained by the model, not just the ones we know about but have chosen to omit.

The situation is somewhat different where there is a need to project future emissions for abatement/mitigation scenarios. Here the policymakers will generally wish to achieve a given reduction in emission with the least cost to society and the industry. Scenarios that include significant structural changes to production systems are usually also associated with major costs and/or political risk. The major structural characteristics of production systems normally map onto the explanatory variables used when compiling emission inventories (e.g. number of dairy cattle, type of livestock housing).

The mechanisms driving emissions of NH_3, CH_4 and N_2O from manure are largely understood; the difficulty is predicting when and to what extent these mechanisms operate in practice. This is because the conditions under which they operate vary with location and time, due to variations in the structure of individual manure management systems and their management. This leads to variations in the parameters of functional relationships that feed through to uncertainties in the resulting emissions. The predictive capacity of any functional relationship depends on the context in which it is to be applied. For example, the development of a technical intervention to reduce emissions may start with an assessment of its potential impact that is based on scientific theory. If this seems promising, development progresses through a range of Technological Readiness Levels (TRL[5]) to a point where it is considered a mitigation measure that has

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[5] https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

been proven to be effective under practical conditions on commercial farms. The uncertainty concerning the nature of the functional relationship(s) in question and their associated parameters may vary as development progresses and more empirical data become available.

There are two main approaches to cost-effectively reflect emission reduction in national inventories. The first is to increase the granularity of the emission inventory, i.e. disaggregate production system categories into a number of subcategories. This may allow the identification of parts of a production system that contribute disproportionately to emissions or where the implementation of mitigation measures would not be technically feasible or would be unusually expensive or cheap. The second approach is to focus on technical measures that can be integrated into the existing production systems. Examples of technical measures are slurry cooling, slurry acidification and the scrubbing of ventilation air. Such measures are either excluded from current emission inventory methodologies or aggregated within the parameterization of broader variables. In the event that a technical measure is implemented in practice, it will be necessary to incorporate the impact on emissions in the inventory (i.e. collect the relevant activity data and document the mitigation efficiency).

2.2 Higher tier methodologies

The advantage of increasing the complexity of the methodology is that it reduces the heterogeneity of the structures and processes driving emissions. For example, dividing the livestock category “Other cattle” into three sub-categories “calves”, “heifers” and “beef cattle” might allow differences in feeding and average age between these categories to be reflected in differences in N excretion. Likewise, dividing livestock housing according to management criteria allows for the effect of this management to be better taken into account. An example of such subdivision can be seen by comparing Table 10.14 (Methane emission factors) of the Tier 2 methodology in IPCC (2006) and the refinement of 2019 (IPCC, 2019), where storage types have been subdivided to take account of the residence time of manure in storage.

However, the accuracy of emission estimates is also dependent on the quality and quantity of the activity and parameterisation data. If the inventory system is not capable of satisfying the increased demand for activity and parameterisation data that inevitably follows the increased complexity of the methodology, then the accuracy of the emission estimates will be lowered.

A fundamental question when considering the development of emission inventories is the level of detail that should be represented in the methodology. There are several factors that determine this level:

1. For categorical variables (e.g. livestock category, manure storage category): Is there a theoretical basis for believing that the level of representation will result in a significant reduction in the intra-category heterogeneity, compared to a more aggregated categorisation?

2. For continuous variables (e.g. dry matter intake, protein concentration in feed): Is there a theoretical basis for believing that its inclusion will result in an increase in the accuracy of the emission estimate?
3. Can the relevant parameters be reliably estimated?
4. Can the input (activity) data be obtained with a sufficient quality?

In modelling terms, the first two questions address modelling error (i.e. the extent to which the method includes all the major driving variables) and the second two address input/parameter error (i.e. the weightings given to those variables). With regard to the need for modifications (refinement) of the 2006 IPCC Guidelines, the "Overview" chapter of IPCC (2019) broadly reflects these four questions in the light of the 2019 refinement the following statements on "Significance and prioritisation criteria":

- Significance of the source/sink and the gas within the sector on a global scale (i.e. sources significant only for a limited number of particular countries, currently or in the foreseeable future, may not meet this criterion).
- Sufficient data availability and maturity of scientific advances since 2006 to provide a basis for methodological development or refinement, including (1) ability to develop new or updated default emission/removal factors; and (2) feasibility of obtaining the necessary data to implement the methods.
- Availability of relevant new scientific results.
- Emergence of new sources or gases meeting these criteria

In an ideal world, a theoretical understanding of the processes driving emissions would be examined in empirical experiments, resulting in a large body of well-balanced data. These data would then be statistically analysed to confirm that the variables tested have a significant effect on the emissions and to estimate the associated parameter values. This information would then be combined with an assessment of the error in the input data required, to quantify the overall uncertainty in the resulting emission estimate.

Unfortunately, for livestock and manure management, there are only large bodies of data available for livestock excretion, enteric CH_4 emissions and the emission of N_2O and NH_3 from field-applied slurry. Even in these cases, the data are biased, since there are many observations from intensive livestock systems in developed countries and far fewer observations from more extensive livestock systems in developing countries (Hassouna et al., 2022). For livestock housing and manure storage, experiments tend to be technically challenging and of long duration, so they are particularly expensive. As a result, the number of empirical data is limited and there is an even greater bias towards well-resourced countries. Livestock housing and manure storage varies between livestock type and between countries, so with a small and unbalanced dataset, it is difficult to obtain statistically significant results for even major explanatory variables, and there is a risk that variables are confounded. One strategy to overcome this situation is to wait until more data are available. However, for a policy area such as GHG emissions, which requires an urgent policy response, this is not an option. In this situation, it is necessary to use theoretical knowledge to identify the major explanatory variables then a combination of the sparse data and modelling for parameterisation. This is indeed the approach adopted for CH_4 emission from manure storage in the IPCC (2019) refinement (see 10B.5 Basis for Changes to MCF Calculations for Liquid/Slurry).

With the IPCC (2019) refinement, it appears that these questions have not been formally addressed, since a number of categorical variables have been increased in detail, without an analysis of the reliability with which parameters can be evaluated or input data obtained. The availability of input data is perhaps less important, since Parties can choose not to use the methodology, if they do not have the data and either cannot or will not pay to obtain it. The exception is if the proposed methodology is intended to be the Tier 2 and the source is a key source, in which case, they are instructed to obtain it. The IPCC (2019) refinement therefore appears mainly an effort to reduce model error. This is understandable, since it is important that all the Parties to the UNFCCC feel that the emission methodologies are capable of reflecting the structure and function of their agricultural systems. However, the accuracy of emission inventories prepared using the methodologies in the IPCC (2019) will only be an improvement over those prepared using IPCC (2006) if the reduced model error is not offset by increased parameter and input error. When considering Tier 3 methodologies, it is therefore important to consider the extent to which the requirements for both parameters and input data are likely to be achievable.

In this document, we examine the scope for increasing the detail of emission inventory methodologies for NH_3, CH_4 and N_2O. In doing so, we consider both the mechanisms underlying the emissions and the extent to which data for input and parameterisation are available in sufficient quantity and quality. The analysis of the manure management data in the DATAMAN database (see D3.1) enabled the development of a range of relationships, relating emissions of NH_3, N_2O and CH_4 to explanatory variables. When assessing the potential for these relationships to form part of Tier 3 methodologies, it is necessary to consider the four points mentioned above on a case-by-case basis.

There can be several reasons for excluding one or more of the models developed in D3.1., in addition to the lack of the availability of input data with sufficient accuracy.

1 Firstly, even if a relationship is statistically significant, it is possible that including it in a particular country's methodology would not materially increase the accuracy of its emission inventory. This might occur if the response to the variable was rather weak and/or the range of the variable in the country was narrow.
2 Secondly, if the range of the variable in a particular country extends significantly beyond that of the data used for parameterisation, the parameterisation could be considered inadequate for that case.

In most instances, it was possible to develop models for emission factors that are based on categorical variables similar to or the same as those used in IPCC (2019). In some instances, the analysis of the data in the DATAMAN database enabled regression equations to be established between emissions and a number of single or multiple explanatory variables (see D3.1). For the single and multiple variable models based on categorical variables, it is self-evident that the models can only be used if the categorical activity data are available. For the single and multiple variable models based on continuous variables, the models can be used to estimate emission factors, provided that the explanatory variables and resulting emission factors remain within the range supported by the data used in the development of each model.

In this current document, we have chosen to assume that the explanatory variables are independent of one another, unless stated otherwise. This means that in some cases, it is possible to combine the single models to improve the accuracy of predicting EFs. However, this assumption would benefit from a rigorous analysis, to assess the importance of the interactive terms.

3 NH_3 emissions

3.1 NH_3 emissions from livestock housing

The NH_3 emission from livestock housing consists both of emissions from urine on the floor of the housing and from manure on the floor and stored in the housing. For the sake of simplicity, in this chapter livestock housing NH_3 emissions are considered as originated from urine on the barn floor. NH_3 emissions from in-house manure storage are considered together with outdoor storage.

The urine contains urea and other low-molecular weight compounds that are rapidly decomposed on the flooring, creating a solution of ammonium that is the source of the NH_3 emission (Cortus et al., 2008). The emission normally occurs within a few hours of excretion.

The main factors driving the emission from flooring are:

- The concentration of N in the urine.
- The area of the soiled surface
- The air flow over the soiled surface
- The temperature of the soiled surface
- The duration of the emission.

The concentration of N in the urine depends on the quantity of protein in the feed ration, the digestibility of the protein, the efficiency with which N is partitioned to production and the volume of urine produced. The latter is dependent on the water balance of the livestock, which is dependent on the intake of ionic salts in the feed ration. The area soiled is dependent on the area to which the livestock have access, the capacity of the flooring to accumulate urine (which depends on the type of flooring and presence of bedding or dung) and whether the volume of urine produced is sufficient to dirty the potential area available. The airflow over the floor depends on the ventilation rate of the building and the interaction between the ventilation air and the internal construction of the building. The temperature of the soiled surface depends on the temperature of the incoming urine and the sensible and latent heat exchange between the floor and its surroundings. The duration of the emission depends on the frequency and efficiency of cleaning and whether livestock are continuously present or are absent for part of the day or part of the year.

Ruminant livestock can tolerate lower air temperatures than non-ruminants. Both types of livestock may encounter problems with high air temperatures but highly productive livestock, such as high-yielding dairy cattle, are particularly vulnerable, since their heat production is much higher. The greater sensitivity of pigs to variations in air temperature mean they are normally kept in housing with forced ventilation whereas cattle, sheep and goats are normally kept in housing with free ventilation. The inside air temperature of housing with forced ventilation, which will often also have heating systems, will be more stable than for housing with free ventilation, since they will be equipped with control systems that regulate indoor air temperature and humidity. The control of freely ventilated housing is constrained by the possibilities offered by the external environment and the extent to which aperture of openings to the outside can be controlled. In addition, this control will usually be manual and not automated, and will be focussed mainly on reducing the risk of excessively low or high temperatures.

3.2 NH_3 emissions from manure storage

In contrast to emissions from urine, the emissions from manure stored on or under flooring will occur over a longer period. The type of manure storage is closely related to the type of housing. Three main types of housing can be recognized in this context:

- Those producing only slurry
- Those producing only solid manure
- Those producing partially-separated liquid and partially-separated solid manures

In slurry-based systems, the urine, dung and any bedding or waste feed is continuously or periodically removed into storage that is either under or adjacent to the flooring. The manure is normally moved by some combination of the action of the feet of the livestock, a scrapper and washing with water. The in-house storage is periodically emptied either into outdoor storage (slurry tank or lagoon) or directly to the fields. Slurry-based systems are typical of larger livestock farms.

In solid manure systems, the excreta and waste feed is combined with a substantial quantity of bedding material (e.g. straw, sawdust) to form farmyard manure (FYM) on a solid floor. No washing water is used but there may be an input of spilt drinking water. The FYM accumulates as a mat on the flooring, under the feet of the livestock, until removed to outside storage (dung heap), processing (composting) or directly to the fields. Solid manure systems are typical of smaller livestock farms or organic farms.

In mixed liquid/solid systems, the livestock typically consist of cattle that are tied head inwards into stalls. Feed is provided at the head end and the floor of the stall is solid, with bedding provided. The stall prevents the livestock from turning and so dung and urine are deposited at the entrance to the stall. The manure is partially separated into solid and liquid fractions. The dung, waste feed, bedding and some absorbed urine are removed manually or by scrapper into outdoor storage (dung heap), while the urine (with some dung, waste feed, bedding) drains into channels that lead to a covered liquid store. These systems are typically associated with traditional, small-scale cattle farming

The main factors driving the emission from storage are:

- The quality of the incoming manure (concentrations of TAN and organic N, manure pH).
- The surface area of the storage
- The air flow over the surface of the storage
- The temperature of the emitting surface
- Biological, chemical and physical processes within the manure.
- The duration of the emission.

The incoming manure consists of excreta (including both undecomposed and decomposed urine), waste feed, bedding, washing water and spilt drinking water. The factors determining the quality of the excreta have been discussed above. The remaining factors are determined by the type of housing and manure storage, and how they are managed.

For liquid manure (slurry, liquid fraction of partially-separated manure), the surface area is determined by the surface area of the storage. For in-house storage in slurry channels or a pit, there may be ventilation or the airflow may be restricted by the presence of the floor above (e.g. slatted floor) or by a lid (partially-separated liquid). For external storage, the airflow is determined by the outdoor environment and by the presence of any crust or cover on the storage. The temperature of the emitting surface will be determined by the energy budget of the storage but is complicated in situations where fresh, often warmer manure is continuously added from above. Manure contains a range of organic compounds that are decomposable under the anaerobic conditions of manure storage. Decomposition of some of these compounds leads to the mineralisation of N to TAN, a reduction in manure DM and changes in manure pH. The potential mineralisation of N depends on the chemical characteristics of the manure while the rate of decomposition depends primarily on the temperature. For intensive pig and poultry housing in temperate climates, the temperature of indoor storage will often be significantly higher than in outdoor storage, during the colder months of the year.

The volatilization of NH_3 decreases the concentration of TAN at the manure surface and in the absence of other mechanisms, would reduce subsequent volatilization. However, TAN will often be replenished by the addition of fresh manure or in liquid manures, the transport of TAN from below. Since the molecular diffusion of TAN is very slow, the main mechanisms driving transport are likely to be the stirring effect of fresh manure input and for liquid manures, the mixing effect of CH_4 and CO_2 bubbles generated in the bulk of the stored manure. Emission is a continuous process, so the duration of emission equates to the length of time that there is manure present in the storage. This period can extend beyond the time that livestock are present in the housing and can continue after the farmer has finished removing manure to outdoor storage or field application, unless any residual manure is removed by washing.

For solid manure, the emitting surface is less well defined, since in the presence of bedding, the soiled surface in contact with the atmosphere can extend below the visible surface of the manure. The same mechanisms operate in solid manure as in slurry, though differently and with some additions. In contrast to slurry, the surface of solid manure may present an aerobic environment, due to the physical structure created by the bedding and for in-house storage, through the mixing action of the feet of the livestock. This may allow for aerobic decomposition, leading to self-heating and further decomposition. Below the surface layer, the environment will be anaerobic, so only anaerobic decomposition will be possible. Beyond the surface layer, there will be little mass transport of nutrients or water, other than the emission of CH_4 and CO_2. Since the C:N ratio of bedding is usually high, decomposition may lead to the immobilization rather than the mineralization of N. A more detailed description of the processes involved is available from Sommer *et al.* (2006).

3.3 Estimating NH_3 emissions

3.3.1 Harmonising IPCC and UNECE Tier 2 methodologies

IPCC (2019) does not explicitly require the determination of NH_3 emissions from livestock housing, with emissions from the flooring of livestock housing, manure stored in livestock housing and in external manure storage aggregated into a single manure storage calculation. There are advantages in at least separating livestock housing emissions (floor and storage) from those from external storage, since different mitigation measures are likely to be applicable to the two situations. UNECE does distinguish between livestock housing and manure storage emissions but in contrast to IPCC (2019), does not require the use of national values for N excretion. Since all countries that report emissions under CLRTP also report emissions under UNFCCC, there is an argument that national N excretion values should also be required in Tier 2 of UNECE. However, to apply the UNECE Tier 2 methodology, it is also necessary to partition the N excretion into TAN and organic N. The excretion of N in faeces depends on the intake and quality of the feed consumed. For cattle and other ruminants, the quality of feed can vary considerably between production systems. For the main categories of cattle (calves, dairy cows etc), there are a range of equations available to estimate faecal N (Dong *et al.*, 2014; Reed *et al.*, 2015), the simplest of which only require a knowledge of the intake of N, which is already a requirement for IPCC. The diet quality of non-ruminants tends to be less variable than ruminants, being based mainly on high-digestibility cereals in intensive farming systems or on food and higher digestibility crop residues in developing countries[6]. For pigs, the faecal N output requires knowledge of the feed intake and the apparent digestibility of the protein (Rigolot *et al.*, 2010).

The form in which the manure is stored (liquid or solid) is a major determinant of NH_3 emission, since systems with liquid manure will expose two soiled surfaces to the atmosphere (floor and in-house storage) whereas systems producing solid manure expose just one, with different management factors affecting the resistance to NH_3 transport between the surfaces and the atmosphere. UNECE separately considers emission from solid and liquid manures while IPCC takes into account the type of storage. However, since IPCC identifies a wide range of storage types and manure stores, the IPCC methodology is in practice more detailed than UNECE. This suggests that there is scope for harmonization between the two emission systems, with UNECE adopting the categories of manure storage used by IPCC.

3.3.2 Higher tier methodologies – livestock housing

The factors determining the NH_3 emission (see NH_3 emission from livestock housing) indicate that the annual NH_3 emission will depend on a range of factors. This includes the type of livestock and their feed ration (influences the quality of the incoming manure and the mineralisation of organic N), the heat generation (influences the ventilation rate necessary to maintain good animal and worker welfare), and the duration of the storage. The emission is also determined by the physical structure of the housing, the external climate and how management responds to the external climate (influences the surface area of the storage, the airflow over the surface of the in-house manure storage and the temperature of the emitting surface). The NH_3 emission is thus determined by a combination of multiple factors and the interactions between them. This means that NH_3 emissions are difficult to predict for a given situation, even with detailed models, and gives rise to a large variation in annual NH_3 emissions, even for a given type of livestock and livestock housing. As a result of this variation, only explanatory variables with a major impact could be detected by statistical analysis.

3.3.2.1 Cattle housing

The analysis of NH_3 emission data from cattle housing in the DATAMAN database[7] (see D3.1) found a significant single variable effect of indoor temperature, housing and floor type combinations, climate zone and ventilation type (forced or free) (see D3.1). With the exception of indoor temperature, these represent

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[6] https://www.fao.org/3/y5169e/y5169e04.htm

[7] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

aggregate variables e.g. housing and floor type combinations represent a combination of the effects of structural and management factors. Inventory compilers therefore have a choice between emission factors categorized according to categorical variables, such as housing type, climate zone or ventilation type, or to estimate emission factors from the indoor temperature, irrespective of these categorizations.

The coefficients for the single and multiple variable models for NH_3 emission from cattle housing are shown in Tables 3 to 7 (see D3.1). The influence of temperature on NH_3 EF including all housing types was tested. The effect of temperature for different housing systems was also tested by grouping temperature and data on NH_3 EFs according the housing types (loose housing, cubicle housing, feedlot and tied stalls[8]). However, for feedlots and tied stalls, temperature data were limited and did not show meaningful relationships. Overall, the modelling results showed that NH_3 emission factors are positively correlated with temperature.

In order to calculate the TAN-based emission factors (NH_3 EF_{TAN}; kg NH_3-N/kg TAN, it is necessary to obtain an estimate of the proportion of the excreted N that is rapidly decomposed to TAN. The mean %TAN in cattle excreta used to convert from the EF (kg NH_3-N/kg N) to the EF_{TAN} (kg NH_3-N/kg TAN),is here assumed to be 42% (Angelidis *et al.*, 2021; Bougouin *et al.*, 2022). The EF_{TAN} values are only available for models that only contain categorical variables.

Table 2: Cattle housing NH_3 EFs estimations (kg NH_3-N/ kg N excreted) for different housing types.

Housing type	NH_3 EFs estimated means*	NH_3 EF_{TAN} (kg NH_3-N/kg TAN)
tied stalls	0.0323	0.077
loose housing	0.0633	0.151
cubicle housing	0.0750	0.179
feedlots	0.2936	0.700

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[8] Categories considered: “tied stalls”; “loose housing” (i.e. deep litter); “cubicle housing”; feedlots

Table 3: Cattle housing NH_3 EFs estimations (kg NH_3-N/ kg N excreted) for different climate zones

Climate zone	estimated means NH_3 EF	NH_3 EFTAN (kg NH_3-N/kg TAN)
temperate wet	0.0598	0.142
temperate dry	0.2593	0.617

Table 4: Cattle housing NH_3 EFs estimations (kg NH_3-N/ kg N excreted) for different ventilation types

Ventilation type	estimated means NH_3 EF	NH_3 EFTAN (kg NH_3-N/kg TAN)
forced	0.0537	0.128
natural	0.1070	0.255

Table 5: Cattle housing NH_3 emission factor (kg NH_3-N/ kg N excreted) dependency on indoor air temperature for all cattle housing types.

Term	Coefficient (EF)
Emission factor	-3.0851
Indoor housing temperature (°C)	0.0395

Table 6: Cattle loose housing NH_3 emission factor (kg NH_3-N/ kg N excreted) dependency on indoor air temperature.

Term	Coefficient (EF)
Emission factor	-4.1126
Indoor housing temperature (°C)	0.0552

Table 7: Cattle cubicle housing NH_3 emission factor (kg NH_3-N/ kg N excreted) dependency on indoor air temperature.

Term	Coefficient (EF)
Emission factor	-2.7492
Indoor housing temperature (°C)	0.0182

3.3.2.2 Swine housing

The analysis of NH_3 emission data from swine housing in the DATAMAN database[9] found a significant effect of manure type (slurry or solid), housing type[10] (for solid manure only) and category of livestock (i.e. grower, finisher, etc.) (see D3.1). For slurry-based systems, there were significant single variable relationships between emissions and the floor type or inside temperature. For solid-based systems, there was a significant relationship between emissions and housing type, livestock liveweight gain per day and temperature. As for cattle, it is necessary to estimate the %TAN in pig excreta, in order to estimate the TAN-based NH_3 emission factors for pig housing. Data on the following variables was downloaded from the Supplementary information in Wang *et al.* (2020): crude protein (CP), average daily intake, N excreted in urine and faeces. The N partitioned to growth was estimated from difference between N intake (=average daily feed intake * %CP in diet/(6.25 * 100)) and the total N in excreta (= faecal N + urine N). Only data where all input variables are available were used. The N use efficiency (NUE = growth N/N in intake) of some data from some sources are either impossibly low (negative) or high, so set a limit of 60% (rounded up from value of potential NUE of 57% in Millet *et al.*, 2018). This gave an estimated mean %TAN in excreta of 67%. The models of NH_3 emission factors for pig housing are shown in Tables 8 to 13.

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[9] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

[10] Categories considered: "deep pit house (and other slurry-based systems); "deep litter with forced ventilation"; "deep litter with natural ventilation"

Table 8: NH_3 emission factors (kg NH_3-N/ kg N excreted) for pig housing based on manure type, housing type and pig sub-category

Manure type	Housing type	Swine sub-category	NH_3 EFs estimated means	NH_3 EFTAN (kg NH_3-N/kg TAN)
Slurry (& unsure)	Deep pit house	Growing swine (growers & finishers	0.1762	0.263
		Growing swine (weaners)	0.1117	0.167
		Breeding sows	0.0921	0.137
		Gilts	0.1554	0.232
Solid	Deep litter forced vent house	Growing swine (growers & finishers	0.2633	0.393
		Growing swine (weaners)	0.1285	0.192
		Breeding sows	0.1454	0.217
	Deep litter natural vent house	Growing swine (growers & finishers	0.1163	0.173

Table 9: Coefficients for NH_3 EF (kg NH_3-N/kg N excreted) from swine housing systems with different floor types and that produce slurry

Variable	coefficient	Coefficient (EF)
Floor type	Intercept (partially slatted)	-2.22
	slatted	0.39

Table 10: Coefficients for temperature-dependent NH_3 EF (kg NH_3-N/kg N excreted) from swine housing systems that produce slurry.

Variable	coefficient	Coefficient (EF)
Mean housing temperature (°C)	intercept	-3.01
	Mean housing temperature	0.05

Table 11: Coefficients for NH_3 EF (kg NH_3-N/kg N excreted) from swine housing systems that produce solid manure

Variable	coefficient	Coefficient (EF)
Liveweight gain per day (kg lwt gain/head/d)	intercept	-3.56
	Liveweight gain per day	2.64
Housing type	Intercept (Deep litter forced vent house)	-1.69
	Deep litter natural vent house	-0.51
Type of bedding material	Intercept (sawdust)	-2.27
	straw	0.72
	woodchips	0.05
Ventilation system	Intercept (forced)	-1.68
	natural	-0.51

No multivariable models were found for slurry-based systems. Those for solid manure systems are shown in Table 12 below.

Table 12: Coefficients for multivariate models of NH_3 EF (kg NH_3-N/kg N excreted) for swine housing systems that produce solid manure

Key variables	Coefficient (EF)
Intercept (forced, sawdust)	-3.985
Liveweight gain per day (kg lwt gain/head/d)	2.723
Ventilation system (natural)	-0.447
Type of bedding material (straw)	0.753

3.3.3 Higher tier methodologies – manure storage (cattle and swine)

Manure can be stored both inside the livestock housing and outside. The emissions from inside storage will be included in the housing emissions (see above). For outside storage, we would expect NH_3 emission to be influenced by the characteristics of the manure (e.g. TAN concentration) and for there to be increases in emissions with increases in temperature, wind speed, surface area and duration of storage. The analysis of NH_3 emission data from the DATAMAN database[11] found a significant effect of duration of storage, manure DM, manure organic C, manure pH, manure TAN and (for slurry only) manure total N and air temperature (see D3.1).

Based on the analysis of the data in the DATAMAN database, the following models for NH_3 emission factors based on categorical and continuous variables were developed (Table 13 and Table 14). It was not possible at this time to estimate EF_{TAN} for manure storage, as there were insufficient data concerning the concentration of TAN in the manure input.

Table 13: Model of NH_3 emission factors (kg NH_3-N/ kg N excreted), based on categorical variables

Storage type	Manure type	Livestock type	NH_3 EFs (kg NH_3-N/ kg N excreted)
Slurry tanks	slurry	Cattle & swine	0.0497
Slurry pits below animal confinements	slurry	Swine	0.0553
Manure heaps	solid	Cattle	0.061
Lagoons	slurry	Swine	0.108
Manure heaps	solid	Swine	0.125

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[11] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

Table 14: Functional relationship describing the influence of measurement duration (=storage duration) on NH_3 emissions (kg NH_3-N/kg N stored) for cattle and swine slurry stored in slurry tanks

key variables	Coef.
Intercept	0.0145
Measurement duration (days)	0.000354

Table 15: Estimates of the fixed effect coefficients for NH_3 emissions (kg NH_3-N/kg N stored) from cattle and swine slurry stored in slurry tanks and pits. Base model is examining cattle.

Variable	coefficient	value
Manure organic C concentration (kg Org C/t fresh wt)	Intercept (cattle)	-2.392804
	Manure organic C	-0.026533
Manure pH	intercept	-8.5177
	Manure pH	0.7387
Manure total N concentration (kg N/t fresh wt)	Intercept (cattle)	-2.53687
	Animal type (swine)	-0.78477
	Manure total N	-0.04932
	interaction	0.12843
Manure TAN concentration (kg TAN/t fresh wt)	Intercept (cattle)	-2.59495
	Animal type (swine)	-0.68999
	Manure TAN	-0.09899
	interaction	0.21260
Air temperature (°C)	Intercept (cattle)	-3.78262
	Animal type (swine)	0.66349
	Air temperature	0.04416

Table 16: Estimates of fixed effect coefficients for NH_3 emissions (kg NH_3-N/kg N stored) from cattle and swine solid manure stored as manure heaps, based on significant fixed effect models ($p < 0.05$). Base model is examining cattle; for swine an intercept needs to be added to the equation.

Variable	coefficient	value
Manure DM concentration (%)	Intercept (cattle)	-1.62180
	Animal type (swine)	1.19622
	Manure DM concentration	-0.05050
Manure organic C concentration(kg Org C/t fresh wt)	Intercept (cattle)	-2.188250
	Animal type (swine)	24.014274
	Manure organic C	-0.010858
	Interaction	-0.167847
Manure pH	Intercept (cattle)	13.1999
	Animal type (swine)	-33.3215
	Manure pH	-2.1028
	interaction	4.1426
Manure TAN concentration(kg TAN/t fresh wt)	Intercept (cattle)	-5.0408
	Animal type (swine)	3.7100
	Manure TAN	1.9985
	interaction	-2.4396

The following multiple-variable models could be developed for NH_3 emission from manure storage (Table 17 and Table 18).

Table 17: Functional relationship describing NH_3 emissions (kg NH_3-N/kg N stored) for cattle and swine slurry stored in slurry tanks, pits or experimental vessels

Key variables	Coef.
intercept	-5.444
Manure DM (%)	0.288
Manure TAN concentration (kg TAN/t fresh wt)	0.079
Air temperature (°C) (average over entire experiment)	0.056

Table 18: Functional relationship describing NH_3 EF (kg NH_3-N/kg N stored) for cattle and swine solid manure stored in heaps and experimental vessels

Key variables	Coef.
intercept	-7.365
Manure Organic C concentration (kg Org C/t fresh wt)	-0.050
Manure pH	0.711
Manure TAN concentration (kg TAN/t fresh wt)	2.067

4 N_2O emissions

N_2O,is formed both during the nitrification and the denitrification processes in the environment. The 'Leakage' model developed by Firestone & Davidson (1989) shows N_2O, and NO_x losses as leakage flows during nitrification and denitrification (Figure 1).

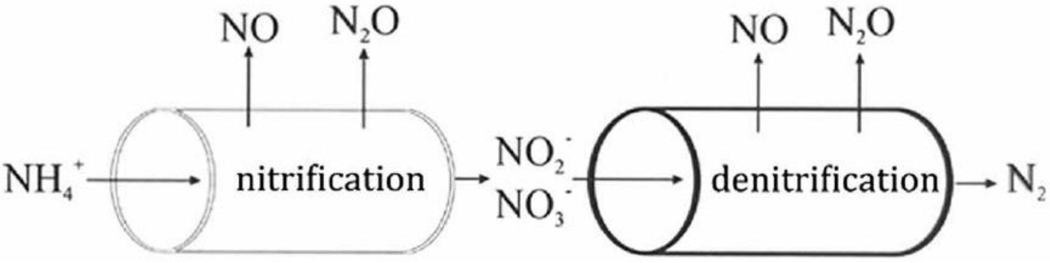

Figure 1. Leakage model for N_2O and NO_x losses during nitrification and denitrification (after Firestone and Davidson, 1989).

Nitrification oxidises ammonia via nitrite to nitrate. This process is strictly aerobic. Autotrophic -nitrifying bacteria belong to the widespread group of Nitrosomonas, Nitrospira and Nitrobacter, which are capable of growing on CO_2, O_2, and NH_4^+. Availability of NH_4^+ is mostly the limiting factor as CO_2 and O_2 are available in abundance. Low pH, lack of P and temperatures below 5°C or above 40°C lead to a reduction in nitrification activities. A water content of 60% of soil water holding capacity is optimal for the nitrification process.

At low pH values, nitrification is carried out by bacteria and fungi. In contrast to the autotrophic nitrifiers, they need carbon sources for their growth. Their turnover rate is much lower compared to the autotrophic nitrifiers, but a substantial total turnover can still be achieved as a wider range of species have the ability for heterotrophic nitrification. N_2O production during nitrification is around 1%, NO_x production ranges between 1% and 4 % of N inputs (Butterbach-Bahl et al., 2011a)

Denitrification reduces nitrate to N_2O, NO, or N_2 when oxygen availability is low. NO_3^-, NO and N_2O serve as alternative electron acceptors when O_2 is lacking, and hence the denitrification occurs only under strictly anaerobic conditions. Molecular N_2 is the last part of the denitrification reaction chain and it is the only biological process that can turn reactive nitrogen into molecular N_2. Denitrifying bacteria are heterotrophic and facultative anaerobic. This means that they use O_2 as electron acceptor and switch to alternative electron acceptors (NO_3^-, NO, and N_2O) when oxygen availability is low. Denitrifying bacteria are widespread and show a high diversity.

Controlling factors for denitrification have been extensively investigated, mainly under lab conditions. Complex interactions exist between the various influencing factors which make a prediction of N_2O emissions difficult under practical conditions.

Denitrification is mainly governed by oxygen availability. Denitrification starts when the O_2 concentration decreases to below 5% (e.g., Hutchinson & Davidson, 1993). This may be the case in poorly aerated soils (e.g., high water content, in excess of 80% water-filled pore space), but also in soils where a high biological turnover consumes the oxygen faster than the supply. Easily degradable carbon sources and high nitrate concentrations also enhance the denitrification rate, while low temperature and low pH limit denitrification activity.

The relationship between N_2 and N_2O formation is mainly governed by the relationship between electron acceptor and reducing agent, and by the O_2 concentration in the substrate. N_2 is only formed under strictly anaerobic conditions and a wide C : NO_3^- ratio. High nitrate concentrations increase the rate of N_2O production. These differences have effects in practice concerning N losses from housed livestock and manure storage, according to the extent of oxygen and carbon availability in different systems. The spatial and temporal distribution of O_2 supply and O_2 demand are of particular importance for the prediction of N_2O emissions (Petersen and Sommer, 2011).

Large proportions of manure N are in an organic form, which must be mineralised to NH_4^+ before becoming a potential source of N_2O. Thus, the organic N pool does not contribute significantly in the short term. It is relevant to consider the concentration of TAN, together with the fraction of the organic N that can be mineralised within the time that a given source has a potential for N_2O emissions.

The emission of N_2O from manure requires the co-location of oxygen, TAN, carbon and the microorganisms, so that partial or complete nitrification and denitrification can occur. Since TAN, carbon and the microorganisms are ubiquitous in livestock housing, the potential for N_2O emission is mainly determined by the supply of O_2 and the duration of the storage. The extent to which this potential is realised depends on the activity of the microorganisms, which is in turn dependent primarily on the temperature and on the C content of the manure. This means that whereas the emission of NH_3 from livestock housing is almost exclusively determined by physical and chemical processes, the emission of N_2O is predominantly determined by biological processes.

4.1 N_2O emissions from livestock housing

In animal houses with slurry collection, the manure remains in a predominantly anaerobic state with little possibility for the NH_4^+ to be nitrified. N_2O could be produced at the air-liquid interface of slurry, but it is on slats and solid floors where urine and faeces are deposited that most of the emissions occur. In fact, housing emissions of N_2O are related to the area soiled by the animals, since there many interfaces between manure and air can occur. Emissions of N_2O are affected by TAN and C concentration and by the pH. High NH_3 concentrations caused by urine can inhibit nitrification, and thus N_2O emissions (Webb et al., 2012).

The bedding can play a role in absorbing urine and keeping the mixture aerated, as well as providing large amounts of degradable C, thus raising N_2O emissions. Here, some degree of compaction seems to be key: when manure is only stored for a short time in the house, there is little opportunity for it to become compacted by the cattle and the conditions remain fully aerobic, thus originating low N_2O emissions. The potential for production of N_2O in pig deep litter is usually greater, due to lower compaction and higher air exchange (Webb et al., 2012).

4.2 N_2O emissions from manure storage

The bulk of slurry (stored outside or inside) is mainly anaerobic, and therefore emissions of N_2O via nitrification and denitrification from slurry without a floating cover are insignificant (Sommer et al., 2000). However, a natural or artificial permeable crust on top of the stored slurry can become a mosaic of anaerobic and aerobic sites, thus creating good conditions for N_2O emission (VanderZaag et al., 2009). For slurry stored outside and covered with a porous material, N_2O emissions increase when evaporation exceeds rainfall, because dissolved NH_4^+ can be nitrified in oxidizing spots, while nitrated can be denitrified in anoxic pockets. When rainfall exceeds evaporation, NH_4^+ in the surface is leached downward and the environment is mainly anaerobic, limiting the potential for N_2O emissions. The use of "low technology" floating covers made of organic materials usually shows an increase in N_2O emissions. However, the number of records related to emission changes for N_2O due to store covers is sparse and these findings can be uncertain. Pig slurry exceeds emissions of cattle slurry in most cases. The data also point at an increase in N_2O emissions when the slurry is acidified, but this is based on limited data and needs further investigation. Many studies also found a strong increase in N_2O emissions related to slurry aeration treatments (Kupper et al., 2020).

Solid manure heaps can be a source of N_2O, especially at the beginning of storage, before the temperature increases. NO_2^- and NO_3^- are found in the surface layers of most heaps, and in consequence emissions of N_2O have been measured from dung heaps. During the composting phase, little N_2O is produced, because of NH_3 volatilisation and because nitrifying and denitrifying microorganisms are not thermophilic (Chadwick et al., 2011). However, favourable conditions for nitrification-denitrification may be re-established when the temperature has declined.

4.3 Estimating N_2O emissions

Nitrogen in manure is a source of N_2O, and the emissions increase with N concentration. Therefore, N_2O emissions are calculated using a N_2O emission factor (EF), which is a proportion of the N in manure (Petersen and Sommer, 2011). The level of detail and methods chosen for estimating N_2O emissions from manure management systems depend on national conditions.

The Tier 1 method entails multiplying the total amount of N excretion from all livestock species/categories in each type of manure management system by an emission factor for that type of manure management system. Emissions are then summed over all manure management systems. The Tier 1 method is applied using IPCC default N_2O emission factors, default nitrogen excretion data, and default manure management system data

A Tier 2 method follows the same calculation equation as Tier 1 but would include the use of country-specific data for some or all of these variables. For example, the use of country-specific nitrogen excretion rates for livestock categories would constitute a Tier 2 methodology.

Tier 3 inventories are advanced systems using measurements and/or modelling, with the goal of improving estimations, beyond what is possible with Tier 1 or 2 methods. For example, a process-based, mass balance approach which tracks nitrogen throughout the system starting with feed input through final disposal could be utilized as a Tier 3 procedure. Tier 3 methods for estimating non-CO_2 emissions typically use a combination of models and measurements. Below are the functional relationships and N_2O EFs estimated through statistical analysis of the DATAMAN database data.

4.3.1 Higher tier methodologies - livestock housing

The dependence of N_2O emissions on microbial processes rather than the more rapid physical and chemical processes driving NH_3 as well as the multitude of factors that can cause the formation of N_2O means it is more difficult to relate the emissions to individual factors. Also, the number of data on N_2O emission research is much lower than for NH_3. This is mainly due because N_2O received attention many years later than NH_3 and because measuring N_2O emissions is very challenging. Consequently, in most cases it was possible to relate emissions to categorical variables only, such as housing type, and not continuous variables.

4.3.1.1 Cattle housing

Single variable models of N_2O emission factors for cattle housing that use categorical variables[12] (based on D3.1) obtained from the analysis of the EF of the DATAMAN database[13] are shown in Tables 19 and 20.

Table 19: Model of N_2O emissions (kg N_2O-N/kg N excreted) from cattle housing based on climate zone

Climate zones	N_2O EFs estimated means (kg N_2O-N/kg N excreted)
temperate wet	0.0013
temperate dry	0.0147

Table 20: Model of N_2O emissions (kg N_2O-N/kg N excreted) from cattle housing based on housing type

Housing type	N_2O EFs estimated means (kg N_2O-N/kg N excreted)
tied stalls	0.0015
loose cubicle housing	0.0018
cubicle loose housing	0.0021
feedlot	0.0123

Note that the emission factors were not found to be significantly different.

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[12] Categories considered: “tied stalls”; “loose housing” (i.e. deep litter); “cubicle housing”; feedlots

[13] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

4.3.1.2 Swine housing

For pig housing, by analysing the EF of the DATAMAN database[14], the following single variable models of N_2O emission from slurry based on categorical variables[15] were found (Tables 21-24; see also D3.1).

Table 21: Model of N_2O emission (kg N_2O-N/kg N excreted) from pig manure based on housing type and pig category

Manure type	Housing type	Swine sub-category	mean EF (kg N_2O-N/kg N excreted)
Slurry	Deep pit house	Growing swine (growers & finishers)	0.0101
		Breeding sows	0.0022
		Growing swine (weaners)	0.0029
Solid	Deep litter forced vent house	Growing swine (growers & finishers)	0.0271
		Growing swine (weaners)	0.0684
		Breeding sows	0.0529
	Deep litter natural vent housing	Growing swine (growers & finishers)	0.0267

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[14] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

[15] Categories considered: "deep pit house (and other slurry-based systems); "deep litter with forced ventilation"; "deep litter with natural ventilation"

Table 22: Model of N_2O emission (kg N_2O-N/kg N excreted) from pig housing based on daily pig liveweight gain

Variable (R^2)	coefficient	estimate
Live weight gain per day (kg lwt gain/head/d) (R^2 = 0.27)	Intercept	-0.019
	Live weight gain per day	0.143

Table 23: Estimates of fixed effect coefficients for N_2O EF (kg N_2O-N/kg N excreted) from swine housing systems that produce solid manure.

Variable	coefficient	estimate
Liveweight gain per day (kg lwt gain/head/d)	intercept	0.429
	Liveweight gain per day	-0.250
Housing type	Intercept (Deep litter forced vent house)	0.279
	Deep litter natural vent house	-0.074
Type of bedding material	Intercept (sawdust)	0.350
	straw	-0.125
	woodchips	-0.068
Mean housing temperature (°C)	Intercept	0.527
	Mean housing temperature	-0.012

Table 24: Functional relationship describing N_2O EF (kg N_2O-N/kg N excreted) for swine housing systems that produce solid manure.

Key variables	Coef.
Intercept (Deep litter forced vent, sawdust)	0.492
Liveweight gain per day (kg lwt gain/head/d)	-0.202
Housing type (Deep litter natural vent housing)	-0.089
Type of bedding material (straw)	-0.123

4.3.2 Higher tier methodologies - manure storage (cattle and swine)

Based on the analysis of the data in the DATAMAN database[16], the following models for N_2O emission factors based on categorical variables were developed (Tables 25-26).

Table 25: Model of N_2O EF (kg N_2O-N/kg N stored) values for different manure storage types

Storage type, split by animal type	Manure type	mean N_2O EF (kg N_2O-N/kg N stored)
Slurry tank - cattle slurry	slurry	0.0043
Slurry tank - swine slurry	slurry	0.0045
Manure heaps – cattle manure	solid	0.0101
Manure heaps – swine manure	solid	0.0164

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[16] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

Table 26 Model of N_2O EF values (kg N_2O-N/kg N excreted) for slurry tanks and manure heaps.

Storage types	Manure type	mean N_2O EF (kg N_2O-N/kg N stored)
Slurry tanks	slurry	0.0044
Manure heaps	solid	0.0119

For slurry storage (cattle and swine combined), there was a significant effect of the duration of the measurements (which we equate with the storage period; see Table 27).

Table 27: Functional relationship describing influence of measurement duration (=storage duration) on N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry stored in slurry tanks.

Key variables	Coef.
Intercept	-6.2674
Measurement Duration	0.00715

When considering cattle and swine solid manure separately, there was a significant effect of the duration of the measurements for swine solid manure (Table 28).

Table 28: Functional relationship describing influence of measurement duration on N_2O EF (kg N_2O-N/kg N stored) for swine solid manure heaps.

Key variables	Coef.
Intercept	-5.7024
Measurement Duration	0.0190

We identified five key variables that significantly describe the variation in N_2O EF: manure DM concentration; organic C; C:N ratio; total N; mean temperature. These variables can be considered key variables to include in future studies. Four variables relate directly to manure characteristics (DM, organic C and total N concentration and C:N ratio) while the remaining variable relates to the climatic conditions. All these significant variables were used to explore multiple variable models (functional relationships).

Therefore, we were able to identify five 2-variable significant models (Tables 29-33). 3-, 4- and 5-variable models were investigated, however, no significant models were identified.

Table 29: Functional relationship describing N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry and solid manure using manure DM and organic C concentration.

Key variables	Coef.
intercept	-7.470
Manure DM (%)	0.737
Manure Organic C (kg Org C/t fresh wt)	0.031

Table 30: Functional relationship describing N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry and solid manure using manure DM and manure temperature.

Key variables	Coef.
Intercept	-6.187
Manure DM (%)	-0.034
Manure mean temperature (°C)	0.062

Table 31: Functional relationship describing N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry and solid manure using manure organic C and total N concentration

Key variables	Coef.
intercept	-6.133
Manure Organic C (kg Org C/t fresh wt)	0.005
Manure total N concentration (kg N/t fresh wt)	0.125

Table 32: Functional relationship describing N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry and solid manure using manure organic C concentration and manure temperature

Key variables	Coef.
intercept	-7.954
Manure Organic C (kg Org C/t fresh wt)	0.009
Manure mean temperature (°C)	0.067

Table 33: Functional relationship describing N_2O EF (kg N_2O-N/kg N stored) for cattle and swine slurry and solid manure using manure CN ratio and total N concentration

Key variables	Coef.
intercept	-7.218
Manure CN ratio	0.068
Manure total N concentration (kg N/t fresh wt)	0.148

5 CH_4 emissions

Methane is produced from the decomposition of organic matter only under anaerobic conditions. The production of CH_4 involves degradation and hydrolysis of organic material to simpler organic compounds, which are then degraded to long-chain acids and alcohols. These components are fermented to short-chain acids and H_2, which are transformed to CH_4 and CO_2. The methanogenic stage of the anaerobic degradation of organic matter is carried out by Archaea microorganisms. This means that CH_4 emission is driven by biological processes, as N_2O emission is. The microbial nature of the emission processes implies that associating emissions with single low-level explanatory variables (e.g. temperature) can be difficult.

Nonetheless, methanogenic Archaea are sensitive to abiotic factors such as temperature and pH, and are more slowly growing than most other microorganisms. In this respect, chemical and physical factors play a large role. pH values lower than 6 strongly inhibit methanogenesis. Methane production is strongly temperature dependent and low at low temperatures (Clemens et al., 2006; Cardenas et al., 2021). Temperatures above 15°C strongly increase methanogenesis. However, a precondition for significant CH_4

production at a given temperature is the presence of microorganisms adapted to the temperature and to the chemical composition of the substrate.

The methanogens are obligate anaerobes, i.e. only grow in virtual absence of oxygen. So, the best conditions for methane emission are found in the bulk of the manure (depending on manure management strategies and facilities) and –most of all– in rumens. This explains why the differences between countries in the percentage contribution of CH_4 to livestock emissions mainly reflect different proportions of ruminants relative to other livestock types, and differences in livestock production systems related to the duration of manure storage.

5.1 CH_4 emissions from livestock housing

CH_4 emissions from cattle housing come predominantly from enteric fermentation (Hempel et al., 2020). The contribution of manure to CH_4 emissions from cattle housing is residual but it can be significant, depending on manure management conditions (e.g. retention time inside the barn, temperature, lack of oxygen). The situation is quite different for pigs. CH_4 emissions from pig barns originate for the vast majority from the manure retained in the barn. Unlike NH_3 emission, which is a surface phenomenon, or N_2O emission, which relies in part on the availability of oxygen and therefore tends to occur near the manure surface, CH_4 formation can only occur in the bulk of the manure.

In fact, the few studies of CH_4 emissions from animal housing conducted to date show that slurry stored in pig houses is a significant, though variable source of CH_4. One source of variation is related to ventilation. For example, in pig houses the indoor temperature may be 20-50% lower with natural ventilation than in houses with forced ventilation. Consequently, CH_4 emissions are significantly lower in the naturally ventilated pig houses.

However, also cattle housing can originate significant CH_4 emissions from manure, when slurry or deep litter manure are retained for a long time. In houses with a solid floor and straw bedding, the hooves of cattle tend to compact the litter, so that anaerobic conditions can occur, making deep litters from loose cattle housings a non-negligible source of CH_4. In contrast, manures from open beef feedlots are often so dry that aerobic decomposition does not occur without the addition of water, and anaerobic decomposition is usually negligible.

The few studies on CH_4 emissions from deep litter in pig houses conducted to date indicate that emissions are indeed lower than those from pig houses with slats and slurry tanks. The proportion of bedding material plays a role, as a large proportion of straw can reduce compaction and favour aerobic conditions (Webb et al., 2012).

5.2 CH_4 emissions from manure storage

Production of CH_4 from manure stores is affected by temperature, manure composition and manure management, but also by the microbiota (Chadwick et al., 2011). While the effects of temperature and composition are well reproduced in batch experiments, like those commonly performed in anaerobic digestion studies, the effects of manure management strategies would be better reflected in continuous reactors, as continuous input is the case in reality. When applying the results of batch experiments to manure management systems based on continuous input, we are obliged to assume that there is no interaction between successive inputs (e.g. inhibition of VS degradation due to inhibition by ammonium, lack of adapted methanogens).

In particular, the storage duration and the emptying rate are relevant. If no residual slurry containing adapted methanogens is left at the beginning of a slurry collection period, little or no CH_4 will initially be produced. On the contrary, long storage times favour high emission rates. The length of the period before the onset of significant CH_4 emission varies in relation to environmental factors, most notably the temperature. For example, in the range 5-15°C the emission of CH_4 can be very low for months if no adapted inoculum is present (Massé et al., 2003). At 20°C, the production of CH_4 has been found to start in approximately 3 weeks (Sommer et al., 2007). In contrast, a 7% volume of old slurry rich in adapted methanogens can be sufficient to immediately start CH_4 emission when fresh slurry is added and the temperature is at least 20 °C (Sommer et al., 2007).

Temperature clearly has an effect on CH_4 emissions from manure stores also as a single factor (see section 5), with temperatures < 15°C generally resulting in negligible CH_4 production. This suggests climatic and seasonal effects on CH_4 emissions from manure stores.

Organic matter, which is the source of CH_4, contains lignified organic components that are recalcitrant to hydrolysis and therefore only slowly degradable. Consequently, CH_4 emission is not related to total organic matter, but only to the hydrolysable not lignified fraction (Triolo et al., 2011). So, differences in animal diet can affect CH_4 emissions from manure. For example, dairy cows fed only roughage excrete less digestible VS than cows also fed concentrates, and consequently the CH_4 production potential of their slurry is lower. Pigs, typically fed rations rich in readily digestible organic matter, produce slurry that has a higher CH_4 emission potential per organic matter unit than cattle slurry (Møller et al., 2004; Triolo et al., 2011). This means that litter can potentially have an influence, too. Anaerobically stored manure with abundant straw-litter is likely to produce less CH_4 per carbon unit in the manure than manure without litter, because of the recalcitrant fractions of the organic matter of the straw.

Finally, the cover of manure stores can play a role. Aside from gastight covers, preventing any gas exchange between the manure and the atmosphere, CH_4 oxidation can occur in permeable covers (e.g. naturally formed crusts) at the interface between the liquid medium and the atmosphere. This would then reduce CH_4 emissions to the atmosphere.

5.3 Estimating CH_4 emissions

Tier 1 method only requires livestock population data by animal species/category and climate region or temperature, in combination with IPCC default emission factors, to estimate emissions. Because some emissions from manure management systems are highly temperature dependent, it is good practice to estimate the average annual temperature associated with the locations where manure is managed.

A more complex method (Tier 2) for estimating CH_4 emissions from manure management should be used where a particular livestock species/category represents a significant share of a country's emissions. This method requires detailed information on animal characteristics and manure management practices, which is used to develop emission factors specific to the conditions of the country. Good practice in estimating CH_4 emissions from manure management systems entails making every effort to use the Tier 2 method, including calculating emission factors using country-specific information. The Tier 1 method should only be used if all possible avenues to use the Tier 2 method did not work.

Going beyond the Tier 2 method implies developing models for country-specific methodologies or using measurement–based approaches to quantify emission factors. The method chosen will depend on data availability and national circumstances.

Below, the functional relationships and CH_4 EFs estimated through statistical analysis of the DATAMAN database data are reported.

5.3.1 Higher tier methodologies – livestock housing (cattle and swine)

For cattle housing[17], the only significant explanatory variable found by analysing the DATAMAN database[18] was ventilation type (Table 36; see also D3.1). As stated above, this effect was likely due to the variation in indoor temperature caused by the ventilation systems.

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[17] Categories considered: "tied stalls"; "loose housing" (i.e. deep litter); "cubicle housing"; feedlots

[18] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

Table 34: Functional relationship describing CH_4 EF (kg CH_4/kg VS excreted) based on type of ventilation used in the housing

Ventilation	CH_4 EFs (kg CH_4/kg VS excreted)
forced	0.0545
natural	0.0810

For swine housing[19], it was possible to develop models and calculate EF based on categorical variables (Tables 37-38) and continuous variables (Table 39); see also D3.1.

Table 35: CH_4 EF values (kg CH_4/kg VS excreted) for different manure types and housing types

Manure type	Housing type	Swine sub-category	mean EF (kg CH_4/kg VS excreted)
Slurry	Deep pit house	Growing swine (growers & finishers)	0.047
		Growing swine (weaners)	0.032
		Breeding sows	0.142
Solid	Deep litter forced vent house	Growing swine (growers & finishers)	0.026
		Growing swine (weaners)	0.015
		Breeding sows	0.020

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[19] Categories considered: "deep pit house (and other slurry-based systems); "deep litter with forced ventilation"; "deep litter with natural ventilation"

Table 36: Estimates of fixed effect coefficients for CH_4 EF (kg CH_4/kg VS excreted) from swine housing systems that produce slurry.

Variable (R^2)	coefficient	estimate
Type of forced ventilation air inlets (R^2 = 0.19)	Intercept (duct)	3.87
	Lateral or frontal	0.656
	Porous ceiling	-0.538
Feed conversion ratio (R^2 = 0.10)	Intercept	-4.59
	Feed conversion ratio	0.216

Table 37: Estimates of fixed effect coefficients for CH_4 EF (kg CH_4/kg VS excreted) from swine housing systems that produce solid manure, based on significant fixed effects models ($p < 0.05$).

Variable	coefficient	estimate
Liveweight gain per day (kg lwt gain/head/d) (R^2 = 0.18)	intercept	-5.41
	Liveweight gain per day	2.13
Type of bedding material (R^2 = 0.04)	Intercept (sawdust)	-4.388
	straw	0.434

For slurry-based housing systems, we identified two 2-variable models (Tables 38-39); one was identified for solid-manure systems (Table 40). There is a further non-independence between the types of ventilation inlets and ventilation outlets in the examined dataset. All CH_4 EF observations with porous ceiling inlets are connected to wall or pit fans outlets while all CH_4 EF observations with lateral or frontal inlets are connected to chimney with fans outlets. This essentially leads to two similar 2-variable models with identical coefficients and performance indicators for the key independent variables but with different coefficient and performance indicators for the intercept. Thus, the preference of one model over another will be based on the availability of the data regarding the type of air inlets or outlets of the forced ventilation systems in swine houses.

Table 38: Functional relationship (2-variable model) describing CH_4 EF (kg CH_4/kg VS excreted) for swine housing systems that produce slurry manure

Key variables	Coef.
Intercept (lateral or frontal)	-2.063
Type of forced air inlets (porous ceiling)	-0.754
Feed conversion ratio	-0.347

Table 39: Functional relationship (2-variable model) describing CH_4 EF (kg CH4/kg VS excreted) for swine housing systems that produce slurry manure.

Key variables	Coef.
Intercept (chimney with fans)	-2.817
Type of forced air outlets (wall or pit fans)	0.754
Feed conversion ratio	-0.347

Table 40: Functional relationship (2-variable model) describing CH_4 EF (kg CH_4/kg VS excreted) of swine for solid manure type.

Key variables	Coef.	R^2
Intercept (sawdust)	-5.60	0.23
Liveweight gain per day (kg lwt gain/head/d)	1.939	
Type of bedding material (straw)	0.461	

5.3.2 Higher tier methodologies – manure storage (cattle and swine)

Based on the analysis of the data in the DATAMAN database[20], the following models for CH_4 emission factors based on categorical variables were developed (Tables 41-42).

Table 41: CH_4 EF values (kg CH_4 kg^{-1} VS stored) for cattle and swine slurry tanks and manure heaps.

Storage type	Manure type	mean CH_4 EF (kg CH_4/kg VS stored)
Cattle, slurry tanks	slurry	0.0908
Swine, slurry tanks	slurry	0.0386
Cattle, manure heaps	solid	0.0285
Swine, manure heaps	solid	0.0014

Table 42: CH_4 EF values (kg CH_4 kg^{-1} VS stored) for slurry tanks and manure heaps (cattle and swine data combined).

Storage type	Manure type	mean CH_4 EF (kg CH_4/kg VS stored)
Slurry tanks	slurry	0.0691
Manure heaps	solid	0.0250

Analysis of all data showed that storage duration does not significantly influence CH_4 EF ($p = 0.087$).

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[20] Hassouna et al. (2022). A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. Journal of Environmental Quality, https://doi.org/10.1002/jeq2.20430

We identified five key variables that significantly describe the variation in CH_4 EF: manure DM concentration; VS concentration; C:N ratio; mean manure temperature; air temperature. These variables can be considered key variables to include in future studies. Three variables relate directly to manure characteristics (DM, VS concentration and C:N ratio) while the remaining variables relate to climatic conditions. All these significant variables were used to explore multiple variable models (functional relationships). We were able to identify five 2-variable significant models (Tables 43-47), but no 3-, 4- and 5-variable models.

Table 43: Multi-variable model for CH_4 emissions (kg CH_4 kg^{-1} VS stored) using manure DM concentration and CN ratio

key variables	Coef.
intercept	-4.7596
Manure DM (%)	-0.1267
Manure CN ratio	0.1253

Table 44: Multi-variable model for CH_4 EF (kg CH_4 kg^{-1} VS stored) using manure DM and VS concentration.

Key variables	Coef.
Intercept	-2.0127
Manure DM (%)	-0.5142
Manure VS concentration (kg VS/t fresh wt)	0.0495

Table 45: Multi-variable model for CH_4 EF (kg CH_4 kg^{-1} VS stored) using manure DM concentration and air temperature.

Key variables	Coef.
intercept	-2.7908
Manure DM (%)	-0.1503
Air temperature (°C)	0.0644

Table 46: Multi-variable model for CH_4 EF (kg CH_4 kg^{-1} VS stored) using manure CN ratio and VS concentration.

Key variables	Coef.
intercept	-3.8273
Manure CN ratio	0.1159
Manure VS concentration (kg VS/t fresh wt)	-0.0231

Table 47: Multi-variable model for CH_4 EF (kg CH_4 kg^{-1} VS stored) using manure mean temperature and air temperature.

Key variables	Coef.
intercept	-4.2583
Manure mean temperature (°C)	-0.0795
Air temperature (°C)	0.1954

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