

Ammonia mitigation for economic and environmental benefits

Key messages building on the UNECE Ammonia Workshop, 23-25 June 2025

Informal note ahead of the UNECE Air Convention
'Heads of Delegation' meeting, 20-23 October 2025.

Note submitted by the co-chairs of the Task Force on Reactive Nitrogen¹

Summary: This note shares key messages about the potential benefits for farm businesses of adopting 'low-hanging fruit' for ammonia mitigation. Seen in the context of the €20 billion to €60 billion worth of wasted nitrogen resources (estimated for the EU per year, 2021 to 2024), there are many cost-effective methods for ammonia mitigation. With appropriate investment, these offer profit opportunities for farmers and can be seen as contributing towards a circular economy for nitrogen, decreasing dependence on newly fixed industrial reactive nitrogen, reducing the risks of fertilizer price fluctuations, while abating the adverse effects of ammonia air pollution for human health and ecosystems. Building on discussions at the Brussels Workshop, we show how the costs of several measures are less (and the benefits larger) than currently estimated by the GAINS model, which overestimates the cost of implementing the most cost-effective measures according to the expert assessment.

It is recognized that ambitious ammonia mitigation to reduce adverse effects on health and ecosystems is necessary in some contexts. While there are opportunities for continued innovation, such 'high ambition' measures currently represent a significant cost for farmers that are justified by the wider societal benefits.

We here highlight the opportunity to embrace the low-hanging fruit that are a win-win for farmers and the environment. Among others approaches, and when done well, cost-beneficial methods include precision spreading of manure and fertilizers, improved fertilizer formulation, improved livestock feeding and covered livestock storage.

Overview of the UNECE Ammonia Workshop

1. The UNECE Ammonia Workshop was held on 23-25 June, organized by the Task Force on Reactive Nitrogen (TFRN) and hosted in Brussels by the European Commission. The main goals of the workshop were to:
 - a. present the current draft of the proposal to revise the UNECE 'Guidance document on preventing and abating ammonia emissions from agricultural sources' (ECE/EB.AIR/120, the 'Ammonia Guidance Document', AGD) and to coordinate continued work,

¹ Note prepared with contributions from Mark Sutton, Barbara Amon, Helmut Döhler, Rasmus Einarsson, Shabtai Bittman, Alberto Sanz-Cobena, Andreas Pacholski, Jack Blackiston Houston, Wilfried Winiwarter & Tommy Dalgaard (Advance draft to be finalized).

- b. enable inputs from stakeholders on revision of the draft AGD, and to work on resolving remaining issues in the revision process,
 - c. discuss the wider policy context of ammonia mitigation, including to take-stock of the willingness by stakeholders to adopt actions to reduce ammonia emissions.
- 2. The meeting was attended by 144 participants from 33 countries, of which 55 joined in person in Brussels and 89 on-line. Participants included research organizations, government ministries, European Commission, Civil Society, businesses in the agriculture and fertilizer sectors, and the convention's Centre for Integrated Assessment Modelling (CIAM). Overall, 27 authors of the AGD under revision contributed to the discussions.

Key messages from the Ammonia Workshop

- 3. The overall response of delegates at the meeting was a positive sense of the need to reduce ammonia emissions. Delegates recognized the substantial adverse effects on human health and ecosystems, while acknowledging that emissions of ammonia represent a waste of valuable nitrogen resources from farming systems. There was a strong sense of increasing readiness to act compared with a decade ago.
- 4. It was highlighted that, given the range of fertilizer prices between 2021 and 2024, and based on fluxes from the European Nitrogen Assessment, total emissions of nitrogen in the EU represent a waste of resources worth €20 billion to €60 billion per year (with the high value for 2022-2023 reflecting the increased fertilizer prices associated with the Ukraine war). Recalling that the entire cost of the EU Common Agricultural Policy is around €60 billion per year, it was acknowledged that there is very strong business case for action to reduce nitrogen losses, including ammonia, that can ultimately improve economic competitiveness.
- 5. A background document to the workshop highlighted these issues in relation to opportunities for revision of the Gothenburg Protocol.² That document distinguished between three cases of country experiences (para. 14):
 - a. **International leaders**, who have already reduced ammonia emissions substantially. In these cases, low-hanging fruit of cost-beneficial measures may have already been adopted, so that further emission reduction to meet existing environmental commitments can be challenging, with net costs for farmers.
 - b. **Emerging actors** in ammonia emission reduction, now implementing recent decisions. In these cases, many low-hanging fruit of cost-beneficial measures typically remain available.

² "Policy options and tools for nitrogen management and ammonia emission reductions that could be included in revision of the Gothenburg Protocol" (Also supplied as a background document to the Helsingør Heads of Delegation meeting).

- c. **Parties yet to start** substantial actions to reduce their ammonia emissions. These actions may take advantage of many low-hanging fruit of cost-beneficial measures for farmers.
6. By 'cost-beneficial' for farmers, we mean measures where the total benefits for farmers of reducing ammonia emissions outweigh the costs incurred by farmers. They can also become cost-beneficial by virtue of specific farmer co-benefits.
 7. One of the key messages of the Ammonia Workshop was that the experiences of countries in groups **a** and **b** can be of great benefit for those countries in group **c** that have not yet started. The latest international evidence was shared as a basis for incorporation into the AGD.
 8. The workshop discussed the extent to which the costs of ammonia mitigation could be specified as part of the revised AGD. Some information on costs is present in the existing AGD (adopted 2012), but overall, the authors of the present revision felt that:
 - a. it was not possible to detail comprehensive costs data for all measures, noting that costs may differ significantly across the UNECE region,
 - b. insufficient resources are currently available to allow the authors to develop such cost estimations.

Overall, the conclusion was that it will not be possible to specify ammonia mitigation costs in the revised AGD.
 9. Conversely, it was also recognized by the experts that information on the costs and benefits of ammonia mitigation is essential to inform both policy decisions and investment by business stakeholders. To address this reality, it was agreed by the Task Force to:
 - a. prepare a short note rapidly that outlines the main messages on ammonia mitigation costs and benefits, and which can inform early negotiations by the Parties (this task is fulfilled by the present note),
 - b. raise awareness among the Parties of the need for investment in the work of the Task Force, to lever resources that would allow necessary estimation of ammonia costs as part of the Convention Work Plan,
 - c. raise awareness among the Parties of the need for investment in farmers to reduce ammonia emissions, especially through agri-environment and other financing schemes.

Many ammonia emission measures require prior investment (e.g., capital outlay), with the aim to more than recover costs over subsequent years. Investment is needed to build confidence and accelerate change.

Main messages about revision of the Ammonia Guidance Document

10. It was agreed that the revised AGD will largely retain the existing structure and scope. As this necessitates going beyond the standard UNECE word-limit, two versions will be prepared: a) AGD summary (official document) and b) Full version of the AGD (submitted as an informal document), with the aim that both parts are jointly adopted by the convention (as previously discussed with the Working Group on Strategies and Review, WGSR).
11. The existing system of UNECE Categories 1, 2 and 3 of the AGD is to be retained. It was re-emphasized that these categories are based purely on scientific and technical evidence and do not include cost considerations. This has the advantage of avoiding negotiation based on economic viewpoints that would otherwise influence the categorization.
12. The existing system of describing mitigation effectiveness is retained, whereby a percentage reduction in ammonia emissions of a mitigation method is compared with the ammonia emissions from an unabated reference method.
13. The main changes foreseen as being made to the revised AGD were identified as:
 - a. Some existing measures change their ranking in terms of the UNECE Categories 1, 2 and 3, while some new measures are added.
 - b. Some measures are divided into separate cases, to allow more accurate estimation of mitigation effectiveness.
 - c. A new chapter is included on manure treatment and processing (which was previously missing), which also considers implications for storage and field application of manure.
 - d. A new annex has been developed 'Methods for ammonia measurement and quality criteria', recognizing the need for guidance on methods to quantify ammonia emissions and abatement efficiency. The workshop discussed the value of this annex and how it can be best adapted to meet the needs of Parties and other stakeholders.
 - e. Increased attention is given to a systematic approach to ammonia mitigation, including: i) consideration of 'packages of measures' and how this can improve cost-effectiveness, ii) system-wide effects in the context of the nitrogen cycle, iii) co-benefits and trade-offs with greenhouse gases, iv) perspectives specific to organic versus conventional agriculture, v) different perspectives of cost-effectiveness.

Main messages about the costs and benefits of ammonia mitigation

14. The focus of the Ammonia Workshop was on the costs and benefits *for farmers and other agri-food related businesses*. It was recognized that the societal costs of nitrogen pollution are even larger than the costs to businesses of wasted nitrogen resources. The wider societal costs were previously estimated by the European Nitrogen Assessment at €70 billion to €320 billion annually, including costs for human health, ecosystems and climate. However, these societal costs were not the

focus of the present meeting, which focused on how reducing the wasteful loss of reactive nitrogen from farming systems could contribute to the circular economy with benefits to farmers and other agri-food related businesses.

15. There was broad consensus at the workshop that improving cost and benefit estimates should be prioritized to support policy development and accelerate action by farmers to reduce ammonia emissions.

Counting the benefit of nitrogen savings

16. The workshop discussed how to value the nitrogen savings from reduced ammonia emissions. A presentation from the CIAM reported that GAINS valued the benefit of reduced ammonia emissions at €0.50 per kg nitrogen saved (i.e. €0.41 per kg NH₃). The original intention of this estimation (developed over a decade ago) was that half of the nitrogen saving be counted (based on a fertilizer price of €1.00 per kg N), with the logic that:
 - a. farmers might not utilize all the benefit and
 - b. that manure has a lower nitrogen use efficiency compared with fertilizer (referred to as 'fertilizer equivalence' because organic nitrogen sources like manure solids are not immediately available to crops and because of higher losses to the environment).
17. The discussion noted that:
 - a. all reductions in ammonia emissions represent an increase in total ammoniacal nitrogen, and are therefore available to crops just as with ammoniacal nitrogen fertilizer, therefore the full value of the benefit should be counted,
 - b. nitrogen prices had increased substantially over the last decade, including up to €3 per kg N during 2022-2023, and that the recent savings are therefore substantially in excess of those valued in GAINS.
18. Accordingly, there is a need take account of these increased economic benefits of ammonia mitigation when considering policy options, especially in relation to revision of the Gothenburg Protocol.

Indicative comparison of ammonia mitigation costs

19. Although it is not possible with available resources for TFRN to specify ammonia mitigation costs for all measures and countries as part of the AGD revision, the workshop agreed for experts to share available information with a focus on provision of a fast overall assessment.
20. In order to make this fast assessment achievable (between July and early September 2025), it was agreed to focus on a limited set of UNECE Category 1 measures. This is not to underplay the importance of Category 2 measures, many of which may provide important cost-beneficial options for farmers to reduce ammonia emissions.

This focus was simply a pragmatic one, given the limited time and resources available to the team.

21. In **Table 1**, we make a comparison of recent cost estimates with those currently estimated from the GAINS model, which is as used for cost-benefit assessment by the convention. The results are summarized in **Figures 1 and 2**. It should be noted that the range of values in GAINS reflects different situations between countries (reflecting different economic situations, as well as operating conditions due to factors such as climate or farm sizes).
22. Unless otherwise stated, the values in Table 1 reflect the gross cost of mitigation to farmers expressed as € per kg NH₃ abated (For clarity, this deliberately excludes any cost savings on mineral fertilizer or other benefits). A negative value implies a direct cost saving to farmers. Subtraction of €1.2 per kg N for the fertilizer saving of reduced emission would give the net benefit of a measure including this effect (i.e., equivalent to €1.0 per kg NH₃). Subtraction of €3 per kg N (€2.5 per kg NH₃) gives the net benefit when considering a high fertilizer price scenario illustrated by the situation in 2022-2023.³
23. Some of the values available to us are based on an assessment including other co-benefits to farmers. This applies to data provided from Denmark, which includes co-benefits (e.g., from covered manure storage of reduced water ingress and energy savings). One of the key messages of the present comparison is the need for Parties to *invest in intergovernmental activity to harmonize procedures and reporting of cost-benefit calculations*, which the TFRN is well-placed to conduct.
24. Values of mitigation effectiveness are also listed in **Table 1 (blue font)**. These are shown as a % reduction in emission compared with a reference method (as listed in the Ammonia Guidance Document). The values represent updates expected to be used in the revised Guidance Document, although some modest changes may yet occur before that document is finalized. It may be noted that measures representing a bigger % emission reduction sometimes work out cheaper (€ per kg N abated), since the difference in expenditure can be smaller than the difference in emission reduction. For example, Table 1 shows that trailing shoe (58% reduction) tends to be more cost effective than trailing hose (31% reduction) for this reason.
25. Overall, we can conclude that:
 - a. There are several methods available where the costs of ammonia mitigation are similar to or lower than the benefit by reducing the wasteful loss of nitrogen resources. We refer to these methods as ‘low-hanging fruit’ since they are cost-beneficial ‘no-regret options’ representing a win-win for farmers and for the environment.

³ This nitrogen saving through mitigation does not apply for feeding strategies that reduce N flow in diets. Nevertheless, the Expert Assessment indicates opportunity for negative costs.

- b. The exact costs of a method when expressed in € per kg NH₃ abated (or € per kg reactive N resource saved) vary according to the implementation details and access to markets. The more a method deployed to achieve substantial emission reductions, the lower the costs per kg NH₃ abated. This means that measures tend to be cheaper on large farms or when equipment is shared between farms.
- c. Whether a method is considered cost-beneficial depends on the time horizon of a calculation. Hence initial capital outlay is recouped over each successive year, and a longer time horizon therefore implies lower net costs and larger net benefits. An accounting approach to recognize this is to specify the percentage return on capital investment per year.
- d. Compared with the estimates from GAINS, the expert estimates are mostly smaller, especially for the most cost-effective measures. Indeed, there are currently no ammonia mitigation measures in GAINS that are assessed as being cost-beneficial for farmers (i.e., benefits exceed costs). This indicates that GAINS is expected to overestimate the mitigation costs for a moderate level of mitigation. It also points to the need for investment in updating the estimates in the GAINS model.
- e. We have not focused here on the most expensive measures. However, Table 1 shows that some measures are substantially more expensive than others. In general, the most expensive measures tend to become more expensive (with increasing labour costs), while low-cost measures tend to become more cost-effective (especially when fertilizer prices increase). This also shows the need for innovation to reduce costs, as for example, presented at the Ammonia Workshop by the Netherlands, which reported on innovative cost-effective abatement methods even in a situation where the low hanging fruit had been adopted decades ago.⁴
- f. In practice, countries that are international leaders (group a), have often integrated capital costs for ammonia emission reduction into their national agri-financing systems. In this way, public agri-environment financing not only helps to accelerate the transition to reduce ammonia emissions but also helps towards a sustainable long-term increase in profits by farmers (i.e., the farmer only pays a share of the capital outlay, but recoups all of the return on investment).

26. We provide two appendices to this report:

- a. **Appendix A** describes two simple farm-level stories about investing in ammonia abatement. The stories were developed in partnership with a farm

⁴ Farm-scale results from the De Marke research centre were presented, showing how: a) artificial rain in a cattle stable, b) regulation of air flow using computer controlled blinds according to windiness in a naturally ventilated stable, and c) improved diet management could provide new cost-effective approaches to further reduce ammonia emissions, which are especially needed in the context of the Dutch 'stikstofcrisis'.

advisor and show how ammonia mitigation can be seen in the context of a farm investment plan.

- b. **Appendix B** provides further information on the information presented in Table 1 and Figures 1 and 2.

Conclusions

- 27. Since the Gothenburg Protocol was originally signed in 1999, there has been more than quarter of a century of experience in ammonia mitigation. Whereas ammonia mitigation may have seemed new in the 1990s, it is now a mature area where Parties can have confidence in the measures. There are many 'low-hanging fruit' where the benefits to farmers exceed the costs, especially when seen as part of long-term farm business plans. There are also other co-benefits of measures can also help improve farm competitiveness (e.g., keeping rainwater out of covered manure stores).
- 28. There has been a strong polarization in Europe with a few Parties taking strong action on reducing ammonia emissions, while many other Parties have hardly started, which will find it easy to take advantage of the 'low hanging fruit'.
- 29. At the same time, the urgency of the environmental crisis, with adverse effects of ammonia air pollution on human health and vulnerable ecosystems means that in many cases high-ambition measures are needed. These may go beyond the low-hanging fruit, with significant costs to farmers, but are justified on the basis of wider benefits to society. Nevertheless, recent experience shows that investment in innovation can further bring down costs, again with simultaneous benefits for farmers and environment.
- 30. Sustainable nitrogen management represents a major business opportunity for the UNECE region. In the EU alone, the waste of resources represents a business loss of €20-60 billion annually (depending on prevailing N fertilizer prices). Coupled with the even larger societal costs of nitrogen pollution, there is a very strong case for investment in measures to manage nitrogen better. The TFRN stands ready to provide support, where the benefits of investing in the Task Force substantially outweigh the modest costs. At the same time, investment in farmers is needed that can increase profitability and resilience by transitioning to a nitrogen circular economy, and reducing the vulnerability of both Parties and farmers extreme fluctuations in fertilizer prices.

Table 1: Illustrative comparison of costs to reduce ammonia emissions.

All cost estimates are expressed here at € per kg NH₃ abated. For conversion to € per N saved, multiply the numbers by 1.21. Positive values represent costs to farmers; negative values represent savings. Unless otherwise specified, business co-benefits for farmers for are not included. **Each measure is accompanied by an achievable % reduction in NH₃ emission [% value in brackets] compared with the reference system.**⁵

Example measure	Expert estimation of costs ¹ (€ per kg NH ₃ abated)	Notes on expert estimation	Costs estimated in GAINS ² (€ per kg NH ₃ abated)	Notes on GAINS estimates
Livestock feeding (phase feeding of pigs) [typically <20-30%, to be agreed]	-2.32 to -0.73	Calculated for 2000 or 1500 animal places (AP), respectively.	0.85 to 1.04	Slightly different values for solid and liquid manure systems.
Livestock feeding (reducing crude protein in cattle diet, improved N rumen recycling) [typically <20-30%, to be agreed]	-	-	0.83 to 1.25	Slightly different values for solid and liquid manure systems.
Livestock feeding (phase feeding of poultry) [typically <20-30%, to be agreed]	-	-	0.83 to 1.25	Slightly different values for solid and liquid manure systems.
Animal housing for cattle: V-shaped floor, with urine train & scraper [20-23%]	Dairy cows without heifers: -6.6 to 22.7	Varies by farm size: 1000 to 50 animal places, respectively.	15.4 to 34.4	For dairy cattle housing measures in general
[20-23%]	Dairy with heifers: -2.0 to 28.7	Varies by farm size: 1000 to 60 animal places, respectively.	27.4 to 52.4	For other cattle housing measures in general
Animal housing for pigs: Partially slatted floor [15-40%]	Solid floor no pit beneath: 6.6 to 7.5 ³	For 50-75% solid floor and 12000 to 450 animal places	20.4 to 26.4	Housing adaptation (for liquid manure systems only)
[32-65%] [47-75% if with cooling of manure surface]	With water & manure channel: Sows: 10; Weaners: 5-6; Grow/finish: 2-3	Estimated for new construction ⁴		
Animal housing for pigs: slurry acidification [64%]	1.6 to 14.4 5.2 to 14.1 4.9 to 44.3	A wide range between studies, with lower costs for larger farms	-	
Animal housing for pigs: biological air scrubbing [70-90%] or chemical air scrubbing [>90%]	Biological: 7.7 to 17.8 ³ 6.3 to 8.6 Chem. scrubbing: 24.4 to 28.9 ³ 4.6 to 11.2	Numbers from different studies, with lower costs for larger farms	Liquid manure system: 3.0 to 5.8 Solid manure system: 3.7 to 6.8	
Animal housing for laying hens: manure belts [30-45%, depending on freq of removal]	Non ventilated manure belts 1.0 to 5.0 Ventilated manure belts 1.0 to 7.00	Lower costs for larger farms.	4.2 to 5.3	Housing adaptation for laying hens
Animal housing for laying hens: air scrubbing [70-90%]	13 to 22	Lower costs for larger farms.	9.4 to 11.9	Exhaust air filters for laying hens

Example measure	Expert estimation of costs ¹ (€ per kg NH ₃ abated)	Notes on expert estimation	Costs estimated in GAINS ² (€ per kg NH ₃ abated)	Notes on GAINS estimates
Animal housing: broiler chicken: air to heat exchanger & circulation fans [28%]	-90.5 to -71.6 ³	Very large cost savings reflect co-benefits (e.g., energy saving)	3.2 to 4.2	Housing adaptation for other poultry
Manure storage for cattle: cover on concrete store [68-83%] [solid manure plastic cover: 91%]	Tent: 5.1 to 10.6 Floating foil: 2.5 to 5.2 Natural crust: 0.0		Dairy cattle: 6.6 to 11.2 Other cattle: 3.8 to 8.1	High efficiency covered stores, liquid systems only
Manure storage for cattle: cover on basin or lagoon [47-69%]	Floating foil: 1.75 Floating bodies: 0.45 Natural crust: 0.0		Dairy cattle: 1.9 to 5.6 Other cattle: 1.7 to 4.8	Low efficiency covered stores, liquid systems only
Manure storage for pigs: cover on concrete store [68-83%]	Tent: 8.6 to 13.6 ³ Tent: 1.0 to 2.2 Floating foil: 0.5 to 1.1 Floating bodies 0.45 to 0.45	Lower € per kg NH ₃ abated for pigs than cattle due to higher N content of manure.	Pigs: 4.4 to 14.5	High efficiency covered stores, liquid systems only
Manure storage for pigs: cover on basin or lagoon [47-69%]	Floating foil: 0.36 Floating bodies: 0.45		Pigs: 2.4 to 5.6	Low efficiency covered stores, liquid systems only
Liquid manure application: Cattle Trailing hose [32%]	-0.08 to 0.58 0.2 to 6.0* With acidification: 2.0 to 2.5	* for 1000 to 100,000 m ³ /year. Larger use reduces costs.	Dairy cattle: 2.1 to 3.1 Other cattle: 1.3 to 2.1	Low efficiency methods for improved slurry application
Liquid manure application: cattle Trailing shoe [58%]	-0.47 to 0.38 1.7 to 5.0*	* for 1000 to 100,000 m ³ /year.		
Liquid manure application: Pig Trailing hose [32%]	-0.14 to 4.1*	* for 1000 to 80,000 m ³ /year.	Pigs 1.7 to 2.3	Low efficiency methods for improved slurry application
Liquid manure application: Pig Trailing shoe [58%]	0.4 to 2.0 -0.62 to 0.26	* for 1000 to 80,000 m ³ /year.		
Liquid manure application: cattle Open slot injection [71%]; Closed slot injection [90%]	0.44 to 3.7*	* for 1000 to 100,000 m ³ /year.	Dairy cattle: 1.1 to 1.6 Other cattle: 0.66 to 1.1	High effic. methods for improved slurry application
Liquid manure application: pig Open slot injection [71%]; Closed slot injection [90%]	0.55 to 4.6	* for 1000 to 100,000 m ³ /year.	Pigs 0.88 to 1.2	High effic. methods for improved slurry application
Liquid manure applic: acidification [57%]	2 to 2.5			
Solid & liquid manure applic: immediate ploughing [90%]	Cattle and pig slurry: -0.74 to 0.74		Dairy cattle: 1.3 to 1.9 Other cattle: 0.74 to 1.4 Pigs: 1.5 to 2.1 Laying hens: 0.34 to 0.47; Other poultry:	High efficiency methods for improved solid manure application
Solid & liquid manure applic: immediate or within 4 hour by non-	Cattle and pig slurry: Range of methods 0.5 to 1.5			

Example measure	Expert estimation of costs ¹ (€ per kg NH ₃ abated)	Notes on expert estimation	Costs estimated in GAINS ² (€ per kg NH ₃ abated)	Notes on GAINS estimates
inversion cultivation [45-70%]			0.68 to 0.91	
Solid & liquid manure applic: immediate or within 24 hour by non-inversion cultivation) [30%]	Cattle and pig slurry: Range of methods 3.4 to 6.8		Dairy cattle: 5.1 to 8.0; Other cattle: 2.8 to 5.4 Pigs: 5.9 to 8.4 Laying hens: 1.4 to 1.8; Other poultry: 2.3 to 3.5	High efficiency methods for improved solid manure application
Mineral fertilizer application: Urease inhibitor [60%]	0 to 0.76	Costs vary according to market access and marketing strategies by fertilizer companies	1.8 to 2.0	Low emission urea application

1. For comparison with GAINS see Figures 1 and 2.

2. The GAINS ranges indicate differences between countries in the EMEP modelling area (first to third quartile, in order to remove extremes). The GAINS estimates as supplied for this note incorporated the benefit of N saving at €0.5 per kg N abated (i.e. €0.41 per kg NH₃ abated). However, for this table, GAINS values have been corrected to exclude the N-saving benefits so as to make the values comparable with expert assessment. This allows the visual comparison between Expert and GAINS estimates in Figure 1, and with the red bands indicating the range of potential profitability of the measures.

3. Danish data of Jacobsen and Kai (2022) with with the value of other co-benefits to farmers included.

4. Estimates from the European Commission, BREF (2017).

5. Note that the emission reduction % values draw on different (wider) datasets reviewed by TFRN than those considered for the cost estimates. This means that they are not exactly comparable. While resolving such differences would require significant additional work, that is not expected to alter the overall picture presented.

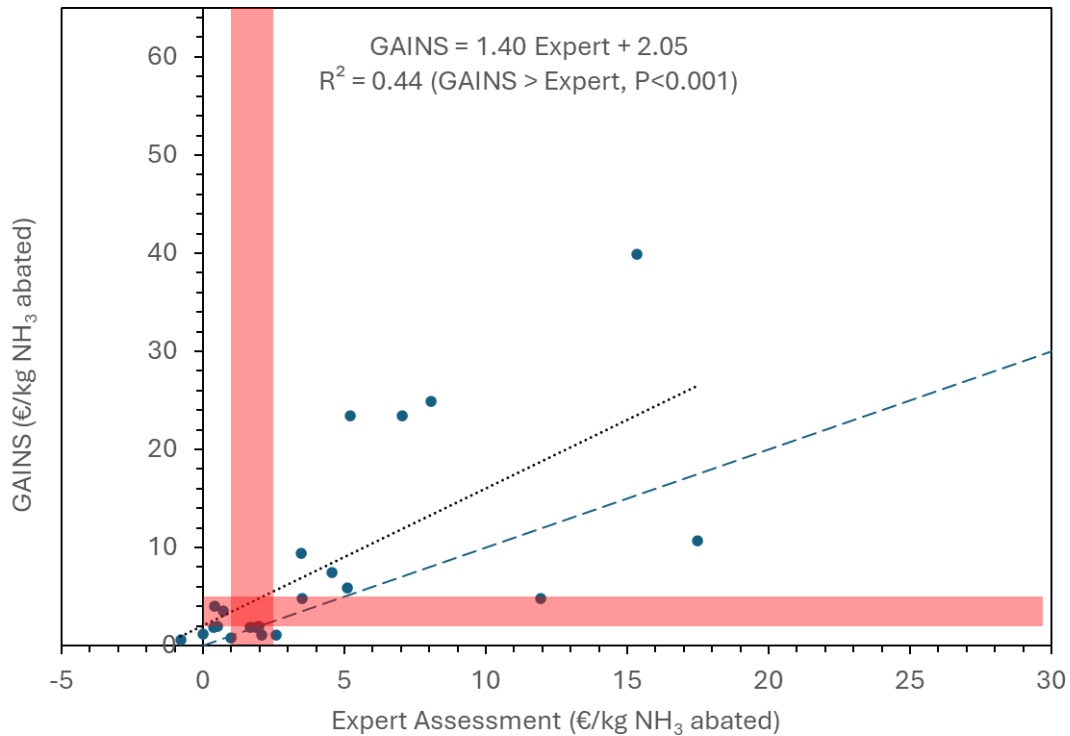


Figure 1: Comparison of costs of ammonia mitigation between expert assessment and current estimates used in the GAINS model.

Lowest costs are generally achieved when implemented on large farms (or when equipment sharing) since this makes better use of capital investment. In some cases, the points shown simply represent the mid-point between low and high estimates.

The figure shows how the unit cost estimates of GAINS are significantly higher than the expert assessment. Combined with other co-benefits than shown here, this indicates that regional mitigation costs are expected to be significantly less than currently modelled over the EMEP area.

Values within or below the red bands can be considered as profitable for farmers, depending on fertilizer prices. The numbers are shown in general excluding the economic value of N savings. This means that values less than c. €1 per kg NH₃ abatement (i.e., €1.2 per kg N saved) offer profit for farmers at current fertilizer prices, while values less than €2.5 per kg NH₃ abatement (i.e., €3.0 per kg N saved) would offer profit for farmers when fertilizer prices are high, as experienced in 2022-2023. Costs may reduce further when considering other co-benefits. Measures with larger costs may still be justified due to the even larger societal costs of nitrogen pollution.

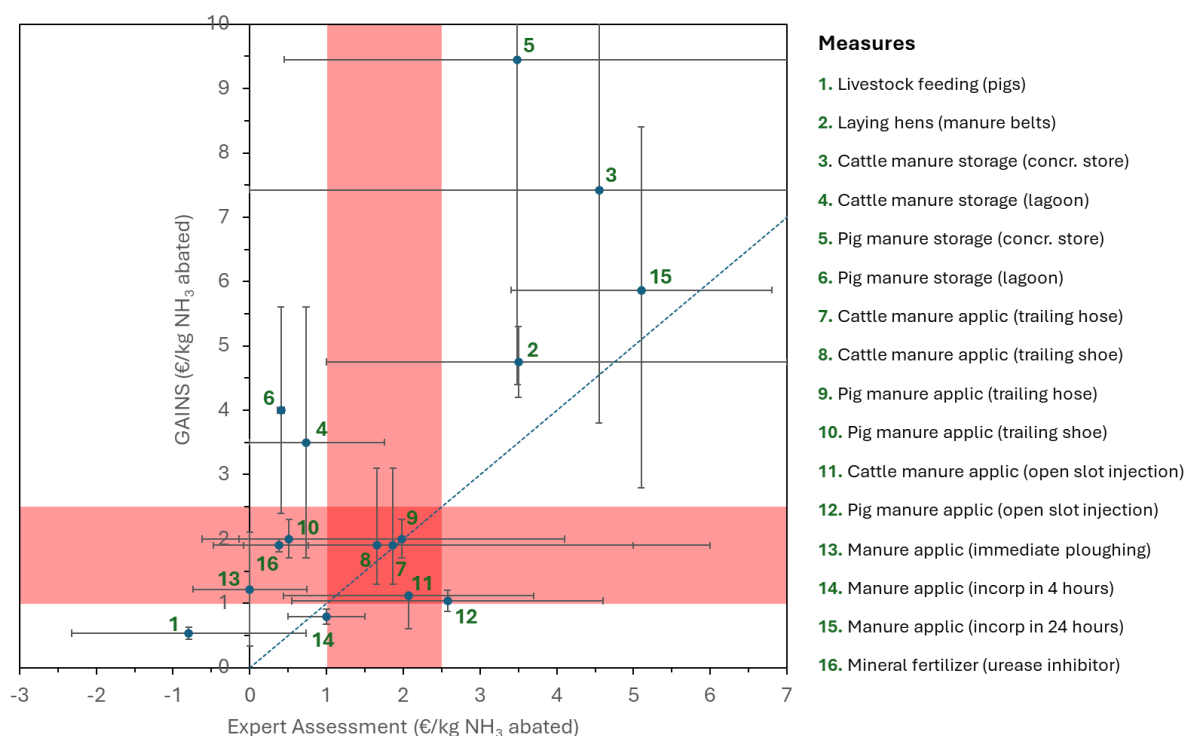


Figure 2: Comparison of costs of ammonia mitigation focused on the measures that are most cost-effective for farmers. Full-cost effectiveness assessment needs also to consider the benefits to society of less pollution (not shown here).

Error bars for GAINS represent the range of values for different countries (first to third quartile, in order to remove extremes). The error bars for expert assessment represent the range of estimates from different studies. The wide ranges of error bars shows that implementation approach matters, with the lowest costs generally achieved when implemented on large farms (or when equipment sharing), since this makes better use of capital investment.

Values within or below the red bands can be considered as profitable for farmers, depending on fertilizer prices. The numbers are shown in general excluding the economic value of N savings. This means that values less than c. €1 per kg NH_3 abatement (i.e., €1.2 per kg N saved) offer profit for farmers at current fertilizer prices, while values less than €2.5 per kg NH_3 abatement (i.e., €3.0 per kg N saved) would offer profit for farmers when fertilizer prices are high, as experienced in 2022-2023.

Appendix A: Simple case studies of how to see ammonia mitigation from a farm business perspective.

The following case studies were developed by a farmer advisor interested in how nitrogen management can inform farm business performance.

1. Should Mr and Mrs Kelly invest in a low-emission manure spreader?

Mr and Mrs Kelly farm 200 milking cows in Co. Down. The cows each produce 9,000 litres per year, and are inside all year round. Additionally, there are 60 maiden heifer replacements, and 60 heifer calves. The remainder of the calves are sold from the farm once tagged.

Currently, the Kellys spread their slurry using a splash plate tanker and are considering purchasing an attachment to change the tanker to a trailing shoe. They have worked out that they have 5,000 m³ of slurry per annum, which contains 1.85 kg of ammoniacal N per tonne per m³. They have been advised by their agricultural valuer that using a splash plate will lose 37% of the nitrogen that could go to the crops, whereas using a trailing shoe would only lose 20% of the nitrogen that could go to the crops. In making the swap, the Kellys would save 1,572 kg of ammoniacal N per annum, which would cost £1,750 per annum to replace in mineral fertiliser per annum (i.e., £1.13 per kg N).

The price for the attachment and fitting of a 10 m trailing shoe is £17,000-20,000 plus VAT, and so in year one the Kellys make up to a 10% return on capital employed, based on a 10-year lifetime.

Comment on the case study: The uniform application will also increase agronomic benefit compared with uneven application using the splash plate tanker. This could save the Kellys 10% on their total fertilizer bill, adding to the economic case, especially if precision dosing methods are used. The trailing shoe also helps to keep the grass sward cleaner enabling cutting sooner, while helping to reduce run-off to nearby watercourses. This saves further N in the farm system, while helping to avoid water pollution, which is a hot-topic in the area due to severe algal blooms in nearby Lough Neagh, see [BBC News](#)). Should fertilizer prices increase again, the Kellys' investment will pay for itself even quicker.

2. Could a 'screw press' help Mrs Morgan manage her manure better?

Mrs Morgan runs a large beef farm with her sons in Wales. Each year they have problems with slurry, which is spread by contractors who complain of the thickness of the slurry and the slowness of the spreading. This costs Mrs Morgan quite a lot of money in contracting spreading costs. There are 300 finishing cattle on the farm, in a 50/50 indoor outdoor system. One of the sons thinks that spending around £70,000 on a 'screw press' separator (separating solids from the liquid) would enable them to reduce costs, and asks their agricultural valuer about this. The valuer says that the unseparated slurry has 1.85 kg of ammoniacal N per tonne, and there is 3000 m³ annually. If a separator was deployed, it would reduce the volume by about 10%, and the remaining slurry would hold 1.9 kg of ammoniacal N in it per tonne. The dry matter content of the slurry would reduce from 7.5% to 5%.

The advisor says that the liquid fraction will infiltrate into the soil better because of its lower dry matter content, which will reduce ammonia emissions by 25%. Even though the volume of slurry has reduced by 10%, this saves Mrs Morgan the equivalent of 145 kg of ammoniacal nitrogen per year, allowing savings on their fertilizer expenditure.

In addition, the contractors are able to spread the remaining slurry at a rate of 150 m³ per hour, rather than the previous rate of 63 m³ per hour. This reduces the number of hours the contractors are spreading by a factor of 2.4, saving 27 hours of contracting work. At a rate of £130 per hour plus VAT, the total saving of the investment is £3,500 per year in spreading costs, plus £160 of fertiliser costs. This gives the Morgan family a return on capital employed of c. 5% in the first year of operation.

Comment on the case study: The case study illustrates how the immediate financial benefits for the Morgans are dominated the opportunity to reduce labour costs, with the nitrogen saving from reducing ammonia emissions providing added benefit. That benefit could be increased by making a 'package of measures' where the Morgans combine the screw-press with other measures, such as uniform application through band spreading and precision spreading of the manure. Should the farm have excessive phosphorus levels, the screw-press also makes the solids more easily transportable to be of increased benefit for other farms, such as for use by a near-by business that produces climate-friendly organic fertilizer pellets.

Appendix B: Further information on ammonia costs

1. **Measures packages.** A farm scale approach with a package of measures can lead to improved effectiveness, reduced mitigation costs and improved fertilizer savings. The following Tables A2.1 and A2.2 (from H. Döhler) also show how unit costs are lower on a larger farm.

Table A2.1: Farm 1: Ammonia emissions, mitigating effects and related mitigation costs in a dairy enterprise with 200 cow places.

		cub. dairy house (CDH)/ open slur. Tank/ broadcast spreading	cub. dairy house/ open slur. Tank/ trailing h., trailing sh, incorpor.	cub. dairy house/ foil cover/ trailing h., trailing sh, incorpor.	CDH/ reduced CP open slur. Tank/ trailing h., trailing sh, incorpor.	CDH/ reduced CP foil cover/ trailing h., trailing sh, incorpor.
Ammonia Emissions (kg NH ₃ *a-1)						
cattle cub house		2.622	2.622	2.622	1.962	1.962
storage		504	504	258	395	202
spreading		5.485	3.448	3.612	2.705	2.833
total emissions		8.611	6.573	6.492	5.062	4.997
delta emission			2.037	2.119	3.548	3.613
extra costs	€/year		3.150	4.950	4.150	5.950
extra costs	€/kg-1 NH ₃		1,5	2,3	1,2	1,6

Table A2.2: Farm 2: Ammonia emissions, mitigating effects and related mitigation costs in a dairy enterprise

		FSF pig fatt/ open slurry tank/ broadcast spreading	FSF pig fatt/ open slurry tank/ trailing hose and incorp.	FSF pig fatt/ foil cover/ trailing hose and incorp.	FSF PF N red feed/ open slurry tank/ trailing hose and incorp.	FSF PF N red feed/ foil cover/ trailing hose and incorp.
Emissions (kg NH ₃ *a-1)						
pig grow/fatt house		7.526	7.526	7.526	6.177	6.177
storage tank		2.523	2.523	387	2.083	319
Spreading		3.575	1.948	2.239	1.608	1.849
total emissions		13625	11998	10153	9868	8345
delta emission			1627	3472	3756	5280
extra costs	€/year		2625	3825	4625	5825
extra costs	€*kg-1 NH ₃		1,61	1,10	1,23	1,10

with 2000 fatterer pig places.

2. **What time-horizon to use when considering scenarios of costs?** In the calculations, the expert approach used here differentiates between investments with different useful lives: 30 years for building structures (e.g. livestock buildings or concrete stores), 15 -20 years for building installations (e.g. slats) and 10 years for technical equipment (e.g. pen partitions).

3. **How does market access affect the price of improved fertilizer formulations?**

Fertilizer prices are not simple, both in term of basic price fluctuations (having some relation to energy prices) and in terms of added costs for enhanced efficiency fertilizers (EEFs), such as including urease inhibitor capability to reduce ammonia emissions. This means that farmers in one country may have access to different fertilizer products and prices than available in another country. In one country (Germany), urea with urease inhibitors has recently been selling with no additional price (to maintain market), since surface urea application without urease inhibitor (UI) is not allowed in Germany. A recent market comparison from France showed the following price differentials, also for nitrification inhibitors (NI) that can reduce soil NO_x emissions:

Granular fertilizer + UI => +40€/t Vs Urea

Granular fertilizer +UI+NI => +60-70 €/t Vs Urea

Urea Ammonium Nitrate +UI => +30€/t UAN

UAN+UI+NI (maybe no such product yet) +45€/t UAN.

Given a baseline emission rate from urea of 20% of the fertilizer lost to the atmosphere, and a 60% reduction of this by use of UI, the additional price works out at €0.72 per kg NH₃ abated. This shows that the method be profitable for at current

fertilizer prices (c. €1.15 /kg N). If UI were marketed at a lower or zero cost (as demonstrated in Germany), then they would be profitable for farmers under a wide range of circumstance. Under cold wet conditions in northern Europe, with lower baseline rates of ammonia emission from urea, UI are likely to be less cost-effective, unless market prices are reduced, as shown in Germany. This warrants more detailed analysis.