ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Urease inhibitors: opportunities for meeting EU national obligations to reduce ammonia emission ceilings by 2030 in EU countries

To cite this article: Yuncai Hu and Urs Schmidhalter 2021 *Environ. Res. Lett.* **16** 084047

IOP Publishing Environ. Res. Lett. 16 (2021) 084047 https://doi.org/10.1088/1748-9326/ac16fe

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
17 April 2021

REVISED
24 June 2021

ACCEPTED FOR PUBLICATION
22 July 2021

PUBLISHED
4 August 2021

LETTER

Urease inhibitors: opportunities for meeting EU national obligations to reduce ammonia emission ceilings by 2030 in EU countries

Yuncai Hu and Urs Schmidhalter

Department of Plant Science, Technical University of Munich, D-85354 Freising, Germany

E-mail: schmidhalter@wzw.tum.de

Keywords: agricultural NH_3 emission, EU 28, policy regulation, NEC Directive, targeted NH_3 emission ceiling, urea fertilizer

Abstract

Anthropogenic NH_3 emissions, primarily from agriculture, have led to significant damage to human health and ecosystems. In the European Union (EU), the National Emission Ceilings (NEC) Directive 2016/2284/EU sets ambitious reduction targets by more than 30% for some countries by 2030 compared to 2005 levels. As urease inhibitors (UIs) can reduce the NH_3 emission from urea by up to 70%, Germany has enforced their addition to granular urea by the national Fertilizer Ordinance since 2020. Therefore, this study investigates the implementation of UIs for urea fertilizers via national policy regulations to evaluate their contribution to achieving the 2030 targets in the EU countries. The results indicate that the contribution of UIs for countries with high reduction targets can reach 20%–60% of the required NEC reduction. The assessment of costs and benefits of UI implementation demonstrates that the ratio of benefits to costs can reach 70. Therefore, we recommend that adding UIs to urea fertilizers is one of the best strategies for mitigation of NH_3 emissions not only in the EU but also in other regions such as China.

1. Introduction

Anthropogenic NH_3 emissions, primarily from agriculture (e.g. 80%–95% in the European Union (EU) in 2018) (EEA 2019), have led to the causes of air pollution, soil acidification, and surface water eutrophication, which can significantly damage human health and ecosystems (Giannadaki *et al* 2018). The total environmental cost of reactive nitrogen was estimated at €75–485 billion year^{-1}, and about 60% of the cost is related to impacts on ecosystems, 40% to impacts on human health (van Grinsven *et al* 2013). Therefore, mitigation of NH_3 emissions has received high priority in the EU.

In 2001, the EU adopted the National Emission Ceilings (NEC) Directive (2001/81/EC) to control major air pollutants (EEA 2019). Most significantly, sulfur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile organic compounds, and particulate matter ($PM_{2.5}$) emissions from 2005 to 2016 fell by 70%, 37%, 28%, and 21%, respectively (EEA 2019). Since 2000, however, only modest reductions of ammonia (NH_3) emissions were achieved in the EU. According to the European Monitoring and Evaluation Programme (EMEP)-Trend from the United Nations Economic Commission for Europe (UNECE) (2020), the observations of air ammonium concentrations showed no significant downward trend for Europe as a whole after 2000. Agricultural NH_3 emissions have exhibited the least reduction. Although agricultural NH_3 emissions decreased by 5% between 2005 and 2013 in the EU, they increased by >3% between 2013 and 2016 (EEA 2019, Giannakis *et al* 2019). Even though a few countries have relatively strict regulations in place, there is no extensive body of EU legislation focused on reducing NH_3 emissions from agriculture. Furthermore, emission projections in Europe also indicate that future ammonia emission reductions will be relatively small if these depend on current legislation (UNECE 2020). In contrast, significant reductions in NH_3 volatilization have been achieved during the last 20 years in some EU member countries such as Denmark, the Netherlands, and the UK through the implementation of environmental policies. In contrast, NH_3 emissions in Spain increased by 14% from 1990 to 2011 (Sanz-Cobena *et al* 2014).

The NEC Directive 2016/2284/EU sets ambitious reduction targets for NH_3 emissions by 2030. For instance, some EU countries are required to reduce NH_3 emissions by >30% by 2030 from 2005 levels. The respective countries must determine policy regulations to mitigate agricultural NH3 emissions to comply with such targets. Germany amended the Fertilizer Act in 2017 and passed a new Fertilizer Ordinance to comply with this NEC Directive. The German Fertilizer Ordinance (BLE 2020) states: 'from 1 February 2020, urea as a fertilizer is applied either with additive urease inhibitors (UIs) or is worked by incorporating urea into soils without delay or at the latest within four hours of spreading urea fertilizer'.

Incorporation of urea application is hindered by constraints such as labor shortage, soil conditions, high plant density, and/or established tree crops or forages at the time of application. Therefore, the addition of UI to urea is the most feasible solution legally targeted by the revised German policy regulation. To the best of our knowledge, Germany is the first country to enforce UI implementation for urea to mitigate NH_3 emissions. The current commercial UIs can effectively reduce enzyme activity to decrease the urea hydrolysis rate. Many studies have shown that such UIs can reduce NH_3 emissions from surface-applied urea fertilizer by 50%–80% (Schraml *et al* 2016, Li *et al* 2017, Silva *et al* 2017, Cantarella *et al* 2018). Moreover, no additional field application facilities are required for the use of urea coated with UI. After the first UI product for urea entered the market in the mid-1990, new and novel UIs that reached the market in the 2000s have increased the UI efficiency by improving the product shelf life and stability at high and low temperatures during the transport, storage, and application (Schraml *et al* 2016, Li *et al* 2017, Pasda *et al* 2017).

The respective contribution of such measures to achieve the 2030 targets and the related benefits and costs for the farmers and the society should be assessed to aid the formulation of specific implementation measures for individual EU countries.

2. Contribution of UIs added to urea fertilizers to NH_3 reduction targets set by the NEC Directive in the EU

Urea accounts for >50% of all synthetic N fertilizers worldwide, and it is the most popular N fertilizer used by farmers because of its high N content (46%), relatively low price per unit N, and relative safety and ease of handling in transportation, storage, and application (Cantarella *et al* 2018). However, urea also has disadvantages, such as the rapid hydrolysis by soil ureases, which can cause NH_3 volatilization. As a result, the global average NH_3 loss from urea fertilizers is estimated to reach 40% (Cui *et al* 2010, Cantarella *et al* 2018).

The NEC Directive 2016/2284/EU requires all EU countries to reduce the NH_3 emissions by an average of 19% by 2030 relative to 2005 levels and sets individual targets for each country.

To reliably analyze the role of UI in reducing NH_3 emissions, we assessed the UI contribution to the NEC target for NH_3 emissions in each EU country (C_{UI}, %) as:

$$C_{\mathrm{UI}}\,(\%) = \frac{(U_{\mathrm{cons}} \times EF_{\mathrm{U}} \times UI_{\mathrm{eff}})}{E_{\mathrm{NH3}}} \times 100\%, \qquad (1)$$

where U_{cons} is the urea consumption of a given country (t/y), $\mathrm{EF_u}$ is the emission factor (EF) of urea (g NH_3–N/kg N applied or %), $\mathrm{UI_{eff}}$ is the UI efficiency for NH_3 reduction from urea-N (%), and E_{NH3} is the targeted reduction of NH_3 emissions for the given country (t NH_3–N/y) from 2017/18 to 2030.

A report from Fertilizer Europe (2021) has indicated that there will be an increase in N fertilizer use across the EU by an average of -0.5% year^{-1} between 2020 and 2030. Therefore, we used 2017 and 2018 U_{cons} data from IFASTAT (2021). NH_3 volatilization from urea is influenced by temperature, soil water content, and soil pH. Therefore, an EF is commonly adopted to quantify global or regional NH_3 emissions from urea. The EF value represents the percentage of applied urea-N that volatilizes as NH_3 (g NH_3/kg N applied or %). According to EEA (2019), EFs of urea N fertilizers in the EU range 15.5%–21% for cool and normal soil pH and warm and high soil pH. In this assessment, an EF of 15.9% for a temperate climate and normal soil pH was used (EEA 2019). Because the UI efficiency ($\mathrm{UI_{eff}}$) ranges within 50%–80% (Schraml *et al* 2016, Li *et al* 2017, Silva *et al* 2017, Cantarella *et al* 2018), 50% and 70% of UI efficiencies ($\mathrm{UI_{eff}}$) for the reduction of NH_3 emissions from urea were considered as the options of UI efficiencies in this study.

Figure 1 demonstrates that the contribution of UI to achieve the NEC targets varies among EU countries, as it is influenced by urea consumption and the specific target value. The assessment of the UI contribution in 2017 and 2018 was similar for most EU countries, which agrees with the expectation that urea consumption in the EU will remain stable until 2030. The addition of UI with 70% efficiency further enhanced the results compared to those at 50%.

According to the NEC Directive 2016/2284/EU, the targeted reduction in NH_3 by 2030 ranges from 0.1 to 187 (10^3 × t NH_3/y). Countries like Germany, France, and Spain have NH_3 reduction targets higher than 10 000 t NH_3/y by 2030. Figure 1 demonstrates that the potential contribution of UI under 50%–70% efficiency for the reduction of NH_3 emissions by 2030 is 44%–69%, 41%–60%, 40%–63%, 32%–50%, 25%–39%, 24%–41%, 10%–17%, and 3% for France, Italy, Poland, Spain, Romania, the UK,

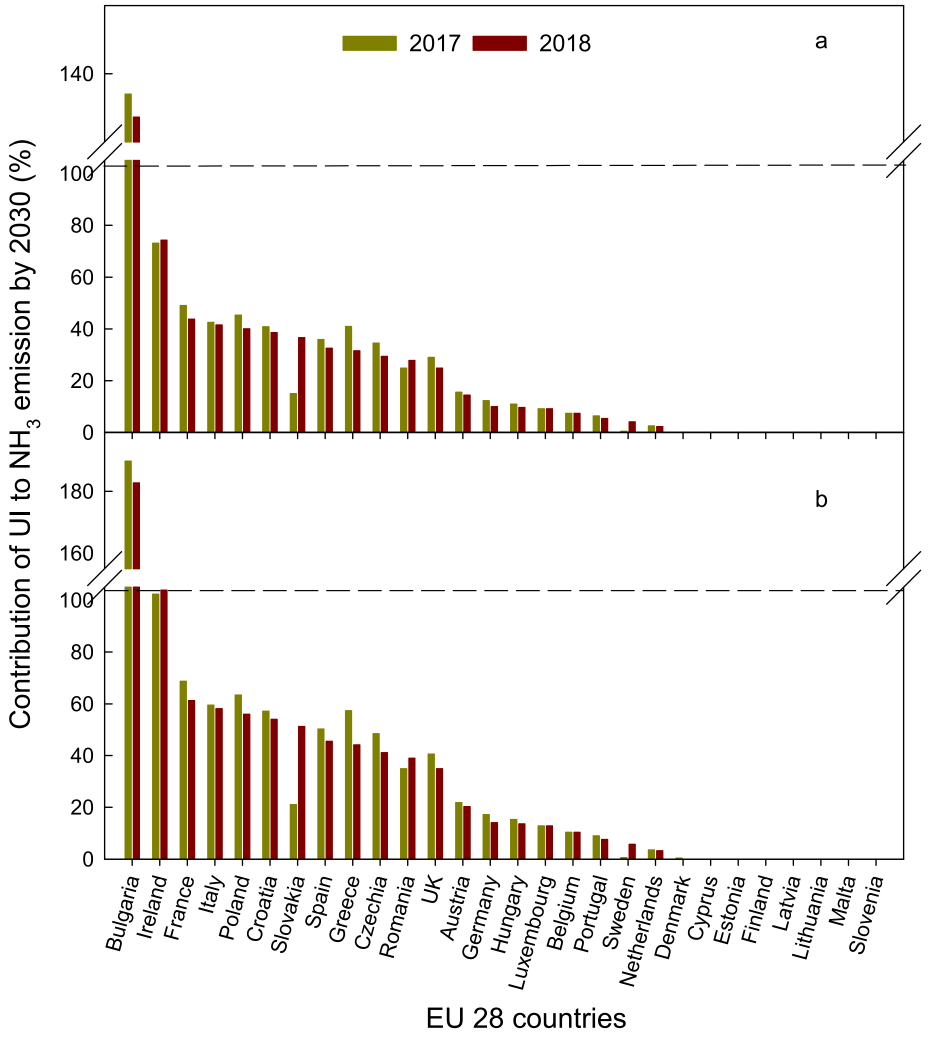

Figure 1. Contribution of UIs with (a) 50% or (b) 70% efficiency for the reduction of targeted NH_3 emissions by 2030 based on the NEC Directive 2016/2284/EU in EU-28 countries. Urea consumption in 2030 was assumed to be similar to that in 2017 and 2018. Missing bars represent very low urea consumption or missing data (data source: IFASTAT 2021).

Germany, and the Netherlands, respectively, based on the urea consumption of 2017 and 2018. For Bulgaria and Ireland, the targeted NH_3 reduction can be achieved if UI with 50% or 70% efficiency is used (figure 1(b)). The assessment of the UI contribution to the NH_3 emission abatements in different EU countries presented in this study can help guide policy priorities.

Among other measures for abatement of NH_3 emission from urea, a ban on urea use suggested in the UK (DEFRA 2020) could be the most effective measure. In Germany, urea amended with UI is still considered the best practice by farmers since it is cheaper than calcium ammonium nitrate. Furthermore, a shift from solid urea to ammonium nitrate fertilizer will increase greenhouse gas emissions through additional direct emissions of nitrous oxide (N_2O) (DEFRA 2020). DEFRA (2020) also reports that the benefit-cost ratio would be highest with the option urea and UI. Although a shift from urea to ammonium nitrate presents a possible option in West Europe, this is still less likely to other regions such as the USA, China, and India, where nitrate fertilizers play only a marginal role.

Furthermore, although inorganic fertilizers could be replaced by organic fertilizers, especially in intensive livestock regions, there is a need to develop low-emission technology to improve organic fertilizer usage. Since manure from livestock farming is responsible for more than 70% of the NH_3 emissions in Europe (DEFRA 2020), abatements of NH_3 emissions in the whole manure management chain, namely, feeding, housing, treatment, storage, and manure application, are required (Sajeev *et al* 2018). Low-emission manure application remains the cornerstone of an effective ammonia abatement strategy being the measure with the largest emission reduction potential. In Germany, low-emission manure application would cover almost 60% of the total technical abatement potential (Wulf *et al* 2017), and similarly, in France, the direct incorporation and injection would offer 60% of the total technical abatement potential (Mathias *et al* 2013, DEFRA 2020, UNECE 2020). Therefore, the low-emission application of slurry in Germany has been mandatory in arable farming since 2020 and is further required in grassland from 2025.

3. Costs and benefits of NH_3 emission abatement by implementing UI added to urea

3.1. Implementation costs

The most widely used UIs in the market are N-(*n*-butyl) thiophosphoric triamide (NBPT), N-(2-nitrophenyl) phosphoric triamide (2-NPT), and a formulation combining NBPT and N-(n-propyl) thiophosphoric triamide (NPPT). UIs are mainly applied as a liquid coating or incorporated into urea granules (UI/urea-N: 0.02%–0.3% w/w). There are generally no additional handling costs for transportation, storage, and field application when urea is coated with UIs. Therefore, the cost of NH_3 emission reduction by UIs (C_{UIR}, € kg^{-1} NH_3) mainly derive from the industrial process used to incorporate UI to urea, which can be estimated as:

$$C_{\mathrm{UIR}} = 1.21 \times \frac{\mathrm{UI_p}}{(\mathrm{EF_u} \times \mathrm{UI_{eff}})}, \qquad (2)$$

where $\mathrm{UI_p}$ is the cost of UI addition to urea (€ kg^{-1} urea-N); $\mathrm{EF_u}$ is the EF of urea (g NH_3–N/kg N applied); $\mathrm{UI_{eff}}$ is the UI efficiency for NH_3 reduction from urea-N (%), and 1.21 is the conversion factor of the cost unit from € kg^{-1} NH_3–N to € kg^{-1} NH_3 (molecular mass ratio of NH_3 to N).

According to DEFRA (2020) and BLE (2020) with industry sources, the addition of UIs to urea accounts for 10% of the urea unit price, i.e. ~0.08 € kg^{-1} urea-N in 2017 or 2018. Contrary to the EF values suggested by EEA (2019), the lowest EF from urea can reach 6% (Schraml *et al* 2016). The EF from urea in China can reach 37% because of high temperatures (Cui *et al* 2010). Therefore, to provide a critical and comprehensive assessment of UI costs, EFs of 5%, 10%, 15%, and 20% were considered, along with 50% and 70% UI efficiencies. The cost assessment values related to UI implementation for NH_3 emission abatement are shown in table 1.

The costs to implement UI for NH_3 emission abatement (€ kg^{-1} NH_3) decrease with increasing EF and with increasing UI efficiency at a given EF (table 1). This suggests that the implementation of UIs can significantly affect regions with higher urea EF, such as China.

Table 1. UI costs of NH_3 emission reduction for different EFs and UI efficiencies.

Options		
EFs	UI efficiency	UI costs
	%	€ kg^{-1} NH_3 reduced
5	50	2.31
	70	1.65
10	50	1.15
	70	0.82
15	50	0.77
	70	0.55
20	50	0.58
	70	0.41

3.2. Human and ecosystem health benefits

The monetization of health benefits can help policymakers devise effective NH_3 emission control programs. The concepts for estimating the social benefits of using UIs mainly deal with the reduction in the damage to human and ecosystem health by NH_3 emissions, since NH_3 emissions adversely affect air pollution to increase air particulate matter $(\mathrm{PM})_{2.5}$ and soil acidification, leading to tremendous damage to human health and ecosystems (Giannadaki *et al* 2018).

Damage costs from different studies are often of limited comparability because of variations in views on what damage should be quantified, dose-response and valuation functions, the release of and exposure to air pollutants in different countries, and scale. Brink and van Grinsven (2011) estimated the health impact cost as 12 € kg^{-1} NH_3 in the EU. Similarly, Wagner *et al* (2017) estimated the costs relative to ecosystems, such as terrestrial biodiversity, as 5–15 € kg^{-1} NH_3. According to the UNECE (2020), the current damage in the EU to ecosystems and human health due to ammonia emissions was monetized by CE-Delft (de Bruyn *et al* 2018), i.e. 17.50 € kg^{-1} NH_3 (margin €10–25.2). The estimates are, amongst others, based on the Health risks of air pollution in Europe (HRAPIE) methodology of WHO (2013) and the valuation of ecosystem damage (Holland and Maas 2014). These external costs include the contribution of ammonia to environmental damage from acidification and eutrophication, particulate matter formation, and related loss of live years. An extensive methodological description can be found in the Environmental Prices Handbook (EU28 version) (de Bruyn *et al* 2018). The damage costs vary across countries and depend amongst others on the population density: in Belgium, Netherlands, and Germany, the damage is estimated at around €30 kg^{-1} ammonia, while in Ireland, Spain and Finland, the damage is less than €10 kg^{-1} based on the robust estimation of social damage of NH_3 emissions by UNECE (2020).

The benefit of NH_3 emission abatement for human health and ecosystems is an average of 17.5 € per NH_3 in the EU, the benefit-to-cost ratio ranges ~7.6–43. As the benefits exceed the abatement costs for all EFs and UI efficiencies analyzed in this study, principally, UIs can be recommended for implementation. In countries with high population density like Belgium, Netherlands, and Germany, the benefit-to-cost ratio will range from 13 to 73. Furthermore, because the social benefits greatly exceed the abatement costs, governments can potentially transfer some benefits to farmers as investment support for the abatement measures.

Additionally, farmers can save urea and obtain higher yields. If urea-N losses of 5%–20% occur from urea application in the field due to NH_3 emissions, approximately 0.02–0.12 € kg^{-1} urea-N can be saved by farmers. In a recent review, Cantarella *et al* (2018) concluded that the yield gain from the use of NBPT with urea varied between 0.8% and 10.2%, depending on the crop species. Cost-benefit analysis of mitigating NH_3 emissions from urea by adding UI by Sanz-Cobena *et al* (2015) showed that a potential grain value of 8.93 € kg^{-1} NH_3–N mitigated was obtained across the EU countries.

UI use can also benefit fertilizer companies. UIs are by far still non-commodity fertilizers (Ramspacher 2017); stabilized N fertilizers, including UIs and nitrification inhibitors, comprise only 8%–10% of the fertilizers used in Europe, 1% in the USA, and only 0.25% in the world (Shaviv 2005). Therefore, regulations such as the one in Germany can help increase UI demand.

4. Application for other regions

Our results indicate that if UI addition to urea fertilizers is implemented in the EU through regulations, its contribution to the targeted NH_3 emission reduction required by NEC in 2030 for countries with high targets can potentially reach 20%–60% (figures 1(a) and (b)). The social benefits-to-costs ratio can reach ∼70. Therefore, adding UIs to urea is one of the best potential strategies to mitigate NH_3 emissions in the EU and other regions.

The UK is currently discussing the UI implementation to urea fertilizers as well (DEFRA 2020). The current propositions include (a) to ban the use of solid urea; (b) impose approved UI incorporation to solid urea before application; and (c) restrict the application of solid urea to the period between 15 January and 31 March (DEFRA 2020). Proposition 2 presents lower estimated costs and a greater benefit-to-cost ratio, and the respective new regulations for NH_3 emission abatement might be adopted in the UK by 2022 (DEFRA 2020).

China consumed 34% of the global urea in 2019, which was around 40% of all synthetic N fertilizers in China, and thus, has the highest quantities of NH_3 emissions worldwide. In contrast to 5% of world NH_3 emissions in the EU, such losses account for 30% in China, before India (24%) and the USA (5.4%) (Zhan *et al* 2021). Muller and Mendelsohn (2007) reported that the cost for health damage in the US ranges from 0.1 to 73 US \$ kg^{-1} NH_3. Its average may be similar to that in the EU. In China, however, the estimation of the cost for health and ecosystem damage is about 6.5 US \$ kg^{-1} NH_3 (Ying *et al* 2017), which is lower than the social damage cost in EU28. This may indicate a lower benefit-to-cost ratio in China compared with that in EU countries. However, NH_3 emission in China is around six times higher than in the EU countries, leading to a high mitigation potential. Zhang *et al* (2020) showed that the current mitigation potential of agricultural NH_3 emissions is 38%–67% compared with 20%–35% in the EU countries. Despite the high losses, China has not implemented regulations to mitigate measures for NH_3 emissions. Our results indicate that countries like China can greatly benefit from implementing UI addition to urea to mitigate NH_3 emissions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgement

This work was supported as part of the GreenWindows4_0 project by funds of the Federal Ministry of Food and Agriculture 516 (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the 517 Federal Office for Agriculture and Food (BLE) under the innovation support program.

ORCID iD

Urs Schmidhalter https://orcid.org/0000-0003-4106-7124

References

BLE 2020 Düngeverordnung 2020 (available at: www.bmel.de/DE/themen/landwirtschaft/pflanzenbau/ackerbau/duengung.html) (Accessed 26 March 2021)

Brink C and van Grinsven H J M 2011 Cost and benefits of nitrogen in the environment *The European Nitrogen Assessment. Sources, Effects, and Policy Perspectives* vol 1, ed M A Sutton, C M Howard, J W Erisman, G Billen, A Bleeker, P Grennfelt, H J M Grinsven and B van Grizetti (Cambridge: Cambridge University Press) pp 513–40

Cantarella H, Otto R, Soares J R and Silva A G D 2018 Agronomic efficiency of NBPT as a urease inhibitor: a review *J. Adv. Res.* **13** 19–27

Cui Z L, Chen X P and Zhang F S 2010 Current nitrogen management status and measures to improve the intensive wheat–maize system in China *AMBIO* **39** 376–84

de Bruyn S, Bijleveld M, de Graaff L, Schep E, Schroten A, Vergeer R and Ahdou S 2018 Environmental Prices Handbook (EU28 version)—methods and numbers for valuation of environmental impacts, CE-Delft

DEFRA 2020 Impact assessment (IA) (available at: https://consult.defra.gov.uk/airquality/implementation-of-cazs/supporting_documents/161012%20%20CAZ%20Impact%20Assessment%20%20FINAL%20consultation.pdf) (Accessed 26 March 2021)

EEA 2019 EMEP/EEA air pollutant emission inventory guidebook 2019 (available at: www.eea.europa.eu/publications/emep-eea-guidebook-2019) (Accessed 26 March 2021)

Fertilizer Europe 2021 Forecast of food, farming and fertilizer use in the European Union 2020–2030 (available at: www.fertilizerseurope.com/wp-content/uploads/2021/03/Forecast-of-food-farming-and-fertilizer-use-2020-2030-Fertilizers-Europe.pdf) (Accessed 16 June 2021)

Giannadaki D, Giannakis E, Pozzer A and Lelieveld J 2018 Estimating health and economic benefits of reductions in air pollution from agriculture *Sci. Total Environ.* **622–3** 1304–16

Giannakis E, Kushta J, Bruggeman A and Lelieveld J 2019 Costs and benefits of agricultural ammonia emission abatement options for compliance with European air quality regulations *Environ. Sci. Eur.* **31** 93

Holland M and Maas R 2014 Quantification of economic damage to biodiversity ECLAIRE Project, Deliverable 18.3

IFASTAT (available at: www.ifastat.org/databases/plant-nutrition) (Accessed 26 March 2021)

Li Q Q, Cui X Q, Liu X J, Roelcke M, Pasda G, Zerulla W, Wissemeier A H, Chen X P, Goulding K and Zhang F S 2017 A new urease-inhibiting formulation decreases ammonia volatilization and improves maize nitrogen utilization in North China Plain *Sci. Rep.* **7** 43853

Mathias E and Martin E 2013 Analyse du potentiel de 10 actions de réduction des émissions d´ammoniac des élevages Français aux horizons 2020 et 2030 *ADEME* (Décembre 2013)

Muller N Z and Mendelsohn R 2007 Measuring the damages of air pollution in the United States *J. Environ. Econ. Manage.* **54** 1–14

Pasda G, Wissemeier A H, Sisay M T, Vance L, Muller M, Sanz-Gomez J, Schneider K H, Staal M, Zerulla W and Schmid M 2017 A novel combination of urease inhibitors and its formulation with better performance concerning biology, handling, transport and storage compared to existing products *Mitt. Ges. Pflanzenbauwiss.* **29** 108–9

Ramspacher A 2017 Assessment of the global market for slow and controlled release, stabilized and water-soluble fertilizers Presentation at IFA strategic forum 2017 (Paris: IFA—International Fertilizer Association)

Sajeev M E P, Winiwarter W and Amon B 2018 Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: abatement options and emission interactions *J. Environ. Qual.* **47** 30–41

Sanz-Cobena A *et al* 2014 Yield-scaled mitigation of ammonia emission from N fertilization: the Spanish case *Environ. Res. Lett.* **9** 125005

Sanz-Cobena A, Vallejo A, Misselbrook T and Wade B 2015 Estimated cost of abating volatilized ammonia from urea by urease inhibitors in the EU *Costs of Ammonia Abatement and the Climate Co-Benefits* ed S Reis *et al* (Berlin: Springer) pp 220–31

Schraml M, Gutser R, Maier H and Schmidhalter U 2016 Ammonia loss from urea in grassland and its mitigation by the new urease inhibitor 2-NPT *J. Agric. Sci.* **154** 1453–62

Shaviv A 2005 Controlled release fertilizers *IFA—International Workshop on Enhanced-Efficiency Fertilizers* (Frankfurt: IVA-International Fertilizer Association) (https://www.fertilizer.org/images/Library_Downloads/2005_ag_frankfurt_shaviv_slides.pdf)

Silva A G B, Sequeira C H, Sermarini R A and Otto R 2017 Urease inhibitor NBPT on ammonia volatilization and crop productivity: a meta-analysis *Agron. J.* **109** 1–13

UNECE (United Nations Economic Commission for Europe) 2020 Assessment report on ammonia—2020 (available at: https://unece.org/fileadmin/DAM/env/documents/2020/AIR/WGSR/Final_Assessment_Report_on_Ammonia_v2_20201126_b.pdf) (Accessed 16 June 2021)

van Grinsven H J M, Holland M, Jacobsen B H, Klimont Z, Sutton M and Willems W J 2013 Costs and benefits of nitrogen for Europe and implications for mitigation *Environ. Sci. Technol.* **47** 3571–9

Wagner S, Angenendt E, Beletskaya O and Zeddies J 2017 Assessing ammonia emission abatement measures in agriculture: farmers' costs and society's benefits—a case study for Lower Saxony, Germany *Agric. Syst.* **157** 70–80

Wulf S, Rösemann C, Eurich-Menden B and Grimm E 2017 Ammoniakemissionen in der Landwirtschaft Minderungsziele und—potenziale Aktuelle rechtliche Rahmenbedingungen für die Tierhaltung, Hannover (KTBL, Thünen) (Accessed 31 May 2017)

Ying H, Ye Y, Cui Z and Chen X 2017 Managing nitrogen for sustainable wheat production *J. Clean. Prod.* **162** 1308–16

Zhan X Y, Adalibieke W, Cui X Q, Winiwarter W, Reis S, Zhang L, Bai Z H, Wang Q H, Huang W C and Zhou F 2021 Improved estimates of ammonia emissions from global croplands *Environ. Sci. Technol.* **55** 1329–38

Zhang X, Gu B, van Grinsven H, Lam S K, Liang X, Bai M and Chen D 2020 Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs *Nat. Commun.* **11** 4357