Preconditions for including the effects of urease and nitrification inhibitors in emission inventories

Governments that have ratified the Paris Agreement (PA) and/or the UNECE Convention on Long-range Transboundary Air Pollution (CLRTP) are under pressure to reduce emissions of greenhouse gases and other atmospheric pollutants such as ammonia (NH_3). Agriculture is a major contributor of nitrous oxide (N_2O), a greenhouse gas, and of NH_3. Synthetic inhibitors were originally developed to increase the efficacy of synthetic nitrogen (N) fertilizers by reducing N losses via gaseous emission or leaching. Urease inhibitors (UIs) reduce the rate of urea hydrolysis to ammonium while nitrification inhibitors (NIs) reduce the rate of biological conversion of ammonium to nitrate. Reviews of published data suggested that UIs and NIs can achieve reductions of ~50% and 35-40% for NH_3 and N_2O respectively (Cantarella et al., 2018; Ruser & Schulz, 2015), so inhibitors have potential as emission abatement measures. UIs and NIs can be applied alone or in combination.

Parties to the PA and CLRTP are required to report their annual emissions to the atmosphere via the Enhanced Transparency Framework and the EMEP Centre on Emission Inventories and Projections, respectively. For the effect of abatement measures to be reflected in emission inventories, a methodology must be developed and then used to calculate the effect on emissions. The methodology must be documented and pass critical examination by independent reviewers. The effectiveness of inhibitors in reducing emissions has been shown to depend on the climate, soil properties, land-use and management conditions under which they are used (Engel et al., 2015; McGeough et al., 2012). Consequently, a comprehensive field campaign of emission measurements under conditions representative of those occurring in a region or country is needed before UIs and NIs can be included as abatement measures in national emission inventories. The importance of evaluating the performance of abatement measures in field experiments has already been considered essential for other environmental measures (EFSA, 2018). Furthermore, a number of countries (e.g. Germany, Ireland and New Zealand) already include the effects of existing commercially-available inhibitors in their GHG emission inventories, supported by field-based emission measurements.

In addition to use with synthetic fertilizers, there is also interest in whether UIs and NIs can reduce NH_3 and N_2O emissions from animal manures (Nugrahaeningtyas et al., 2022) and in the development of novel inhibitors, including biological inhibitors (Subbarao et al., 2013) that could be used in organic farming. Within the European Union (EU), inhibitors are certified and regulated via the REACH regulation and in the USA, nitrification inhibitors are regulated by the Federal Insecticide, Fungicide, and Rodenticide Act, with both focusing on their impact on human and ecosystem health, rather than their efficacy. Within the EU, novel inhibitors are additionally regulated via the EU Fertiliser Regulation, which came into force in July 2022 and was developed to facilitate nutrient recycling as part of the EU's Green Deal. It specifies that a substance can be sold as an inhibitor '*if compared to a control sample where the inhibitor has not been added, an in vitro test containing the inhibitor shows a 20 % reduction in the target activity, based on an analysis carried out 14 days after application at the 95 % confidence level*'. The target activity for a urease inhibitor is the hydrolysis of urea, and NH_3 loss is not measured. The targets for nitrification or denitrification inhibitors are the reduction in ammoniacal N oxidation rate and the release of N_2O, respectively. It is our view that the criteria specified by the EU Fertiliser Regulation only correspond to proof-of-concept testing and, as such, provide a wholly inadequate basis for inclusion in national emission inventories. Taking inspiration from earlier guidance (IPCC, 2000), we outline the criteria that should be fulfilled, before the effects of either current or novel inhibitors, used with either synthetic fertilisers or animal manures, are included in national emission inventories.

Establishing the efficacy of inhibitors

For substances marketed as nitrification or denitrification inhibitors, the necessary protocols for measuring N_2O emissions from soils have already been developed by the Global Research Alliance (GRA; https://globalresearchalliance.org/). These include detailed guidelines relating to the design, construction, and running of a range of emission measurement systems, the frequency of measurements (Grace et al., 2020) and how to analyse results and calculate emission factors (de Klein et al., 2020).

For UIs, guidance on NH_3 emission measurement, equivalent to the GRA guidance for N_2O, is absent. The guidance is currently under development by the Expert Panel on Mitigation of Agricultural Nitrogen, part of the UN Task Force on Reactive Nitrogen. However, temporary guidance is available (https://www.tfeip-secretariat.org/agriculture-and-nature).

We propose that the main elements of the empirical evidence necessary for the effects of current or novel inhibitors to be included in national emission inventories should be:

1. The emission measurement protocol should follow the core scientific principles of measurement of nitrogenous emissions from soils, as indicated above.
2. Emissions should be measured for the specific combination of emission source (e.g. urea, urea ammonium nitrate, and urine, cattle slurry, pig slurry) and inhibitor product formulation (i.e. active ingredient, liquid or solid products, single or double inhibitor).
3. Experimental design should ensure that measurements are made under field conditions representative of the crops, soil types, climates, and management practices under which the inhibitors will be used.
4. Experimental design should at a minimum include paired comparisons (i.e. treatments with and without the inhibitor) so that the relative reduction in target emission can be assessed under the same management and environmental conditions. A zero N control should be included to enable a direct measure of the reduction in emission factor.
5. The duration of the measurement period should at a minimum capture the whole "emission envelope" i.e. from immediately before application until emissions return to background levels, as measured in untreated plots. For NIs this may require a duration of up to a year, depending on climatic conditions and local management practices. The duration for UIs would usually be much shorter, as the duration of NH_3 emissions is normally (but not invariably) a few weeks.
6. Sufficient measurements should be made so that a reliable uncertainty estimate (standard error or confidence interval) can be derived for the reduction efficacy.

Including inhibitor effects in emission inventories

Inclusion of the effects of products containing inhibitors in emission inventories requires that the efficacy is adequately documented, as described above. In addition, documentation of the quantity of each specific inhibitor compound used annually in agriculture is required. This should aim to document actual use, not just a legal obligation for use, since compliance is unlikely to be 100%. The efficacy of some inhibitors can be greatly reduced if handled inappropriately or if dosing rates are inadequate. Consequently, evidence should be provided to show that farmers are adequately advised concerning the storage and application technique of inhibitor products and that suppliers ensure adequate inhibitor dressing rates to fertiliser products, to allow for degradation over the expected storage period. Finally, inventory compilers need to be aware that an abatement measure targeting one pollutant may impact another e.g. NIs may increase NH_3 emissions.

The criteria we propose should not be seen as an attempt to constrain innovation or delay the implementation of abatement measures but as one that addresses the scientific and documentary evidence required to follow good emission inventory practices. Emission reduction commitments made by Parties under the PA and CLRTP in relation to atmospheric emissions from agricultural sources can require them to impose regulations on farmers that are both costly and politically difficult. It is therefore important that there is confidence amongst national politicians, environmentalists and farmers that the measures they take will deliver the reductions in emissions in practice and not just in theory. It is also essential for reducing emissions internationally that Parties retain confidence in each other's emission inventories, which requires Parties to provide the evidence of efficacy described above.

The authors of this article are actively engaged in atmospheric emission inventories as inventory compilers, data providers, reviewers and/or editors of guidance documents. Novel compounds are already being marketed as inhibitors in the EU and we are aware that emission inventory compilers are coming under pressure to include the itemised per inhibitor effects of these compounds in national emission inventories. Ensuring a good alignment between the reductions in gaseous emissions actually achieved at the farm and field scale with abatement measures and the quantitative estimation of such reductions in inventories is a prerequisite to

achieving climate neutrality and clean air targets. Therefore, we encourage emission inventory compilers and reviewers (indeed, all those interested in using inhibitors for emission reduction and efficient use of N fertilisers) to take notice of this article and the material referenced herein, when setting preconditions for including their effects in national emission inventories.

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Competing interests

The authors declare no competing interests.