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Technical opportunities to reduce global anthropogenic emissions of nitrous oxide

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Abstract

We describe a consistent framework developed to quantify current and future anthropogenic emissions of nitrous oxide and the available technical abatement options by source sector for 172 regions globally. About 65% of the current emissions derive from agricultural soils, 8% from waste, and 4% from the chemical industry. Low-cost abatement options are available in industry, wastewater, and agriculture, where they are limited to large industrial farms. We estimate that by 2030, emissions can be reduced by about 6% ±2% applying abatement options at a cost lower than 10 €/t CO_2-eq. The largest abatement potential at higher marginal costs is available from agricultural soils, employing precision fertilizer application technology as well as chemical treatment of fertilizers to suppress conversion processes in soil (nitrification inhibitors). At marginal costs of up to 100 €/t CO_2-eq, about 18% ±6% of baseline emissions can be removed and when considering all available options, the global abatement potential increases to about 26% ±9%. Due to expected future increase in activities driving nitrous oxide emissions, the limited technical abatement potential available means that even at full implementation of reduction measures by 2030, global emissions can be at most stabilized at the pre-2010 level. In order to achieve deeper reductions in emissions, considerable technological development will be required as well as non-technical options like adjusting human diets towards moderate animal protein consumption.

Keywords

Greenhouse gas, climate mitigation, techno-economic analysis, N_2O

Acknowledgements

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1. Introduction

Nitrous oxide, N_2O, is a natural component of the atmosphere. Microbial processes, especially nitrification and denitrification in soil, yield N_2O as a side product. Incomplete combustion, as in wildfires, also leads to N_2O formation. Anthropogenic activities such as combustion processes or adding fertilizer to soils increase these emissions. Purely man-made emissions come from the direct use of N_2O, mostly in anesthetics, and from its release as a by-product of certain chemical industry processes. Anthropogenic impacts have increased total global N_2O emissions by 37% since 1860 (when natural emissions were higher than today: Galloway et al., 2004) and atmospheric concentrations have risen by 20% (Ciais et al., 2013). The contribution of N_2O to current anthropogenic greenhouse gas (GHG) emissions (comparing the Global Warming Potentials of different gases over a 100-year horizon) has been estimated at about 6% (Edenhofer et al., 2014), which places N_2O third among anthropogenic GHGs.

GHG scenarios developed by integrated assessment models have focused on reductions in carbon dioxide (CO_2) emissions through transformation of the energy system (Clarke et al., 2014). To the extent that non-CO_2 GHGs are covered in such models (e.g., USEPA, 2013; Lucas et al., 2007), emission reduction potentials have often been assessed in combination with other GHGs and without presenting individual gases separately. Models that specifically evaluate N_2O emissions and mitigation potentials are either limited to the agricultural sector (Bouwman et al., 2013; Bodirsky et al., 2012), or they do not provide details on specific abatement measures or their regional applicability (UNEP, 2013). These studies, as well as the results of IPCC's "shared socio-economic pathways" scenarios (Riahi et al., 2017), have suggested upward trends in global anthropogenic N_2O emissions. Even at full implementation of available technical options it will remain difficult to bring global N_2O emissions below current levels. This is critical, because in view of the Paris Agreement to limit global warming to "well below 2°C" above pre-industrial temperatures, deep cuts in non-CO_2 emissions will be needed in addition to CO_2 reductions (Gernaat et al., 2015). In this paper we revisit this conclusion by analyzing the current and expected future technological potentials and costs for N_2O abatement with associated uncertainty boundaries in greater technological and geographical detail than previous studies.

A specific focus on N_2O emission trends and their abatement potentials is important for the following reasons: (i) technical abatement options are readily available and can in principle be implemented immediately, and have long been considered cost-effective for addressing the challenge of GHG emissions reductions (Winiwarter et al, 2010); (ii) concentrating on a specific gas (N_2O) helps to validate historical levels and future benchmarks for change by way of independent data (using atmospheric concentration inversions: Bergamaschi et al, 2015). This means that the effects of N_2O as an ozone depleting substance in the stratosphere can be simultaneously addressed (Crutzen, 1970; Ravishankara et al., 2009); (iii) a detailed assessment of the potentials and costs of individual technology options can identify regions and sectors particularly suitable for cost-effective reductions of N_2O emissions.

In this paper we describe specific technology options for which emission abatement potentials and costs can be quantified and which represent clearly identifiable measures. The effects of consumer preferences that may impact the agricultural system and in consequence limit N_2O emissions are beyond the scope of this study.

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2. Method

The GAINS (Greenhouse Gas - Air Pollution Interactions and Synergies) model (Amann et al., 2011) offers a framework for consistently quantifying current global N_2O emissions as well as projecting future emissions and the associated emission abatement potentials and costs. GAINS computes N_2O emissions for 172 regions in 5-year intervals from 1990 to 2050. Many of these regions represent countries, but very large countries consist of several regions, and some small countries or countries with less detailed information available are grouped into regions. For the purpose of this paper, we further aggregate GAINS regional results according to the "world regions" defined for the MESSAGE integrated assessment model[1] that have considerable homogeneity in terms of physical and economic features.

GAINS uses statistical information (for historic years) and external activity projections to obtain information on the important drivers of emissions. For N_2O, these drivers include energy consumption, agricultural production, population, and industrial production. Combining the activity data and projections with emission factors available from the technical and scientific literature results in computed emissions by source sector. Details on the procedure, the available information and data used, including a description of the respective abatement technologies and full references to the respective literature, are provided in the Supplementary Information (Part 1). The baseline scenario for agriculture relies on the projections originating from the FAO (Alexandratos and Bruinsma, 2012), which is conceptually an extrapolation of current trends of animal numbers and fertilizer consumption. This baseline implicitly covers expected improvements in the efficiency of nitrogen use, especially in areas that currently are known to be exposed to excess fertilizer use (and increased fertilizer application in regions of currently very low use). Energy projections have been obtained from IEA (2012), with more detailed information available for Europe (Capros et al., 2016).

The individual abatement technologies considered in the GAINS model to reduce N_2O emissions are listed in Table 1. Region-specific information on emission removal efficiencies and costs have been compiled from the literature and are referenced in the Supplementary Information. To capture the sensitivity of different cost estimates to cost parameter assumptions, we distinguish between investment, operating and maintenance costs, and cost-savings, due to, for example, reduced fertilizer consumption. The ranges in Table 1 represent region- and source sector- specific values. The cost elements for which assumptions are critical include fertilizer prices (fertilizer savings are applied against fertilizer costs) and interest rates for fixed investments in machinery. The latter will apply to some options (e.g., the cost of machinery used for "variable rate technology" (VRT) to save on fertilizer application), but will not be needed for others. Costs related to "nitrification inhibitors" do not include investments but only variable costs for the chemicals that impede the N_2O release rate. In the work presented here, costs are evaluated assuming a fertilizer world market price

[1] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html

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Table 1: Overview of N_2O emission abatement technology implemented in GAINS. Emission reductions and costs are provided as ranges – specific implementation depends on regional parameters, economic side benefits considered as in fertilizer savings, investments and interest rates, farm size structure. Details and specific sources are listed in the Supplementary Information. When different technologies are presented for the same source this indicates that several levels of stringency in emission abatement are considered, which may be taken subsequently (but emission reductions and costs are always compared to the "no control" case).

Source, source sector	Abatement technology	emission reductions	Cost range		Marginal costs [€/ton CO2-eq]
Fertilizer applied to soils*	Variable Rate Technology	19-24%	0.04-0.09	€/kg N applied	5 - 94
	Inhibitors to suppress soil microbial activity	34-38%	0.09-0.19	€/kg N applied	51 - 101
	Optimization of agricultural nitrogen efficiency by "precision farming"	36-40%	0.3	€/kg N applied	775 - 1600
Grazing cattle	Inhibitors to suppress soil microbial activity	24%	0.81	€/animal	298
Farmed organic soils	Abandonment of agricultural use	92%	600	€/ha	174
Livestock/manure handling	Shift from solid manure systems to liquid manure systems	50%	--		
Adipic acid and glyoxal production	Catalytic or thermal reduction	95%	15	€/ton product	0.2
	Twin reduction device technology	99%	31	€/ton product	4
Nitric acid production; Caprolactam production	Catalytic or thermal reduction	80%	0.72	€/ton product	0.6
	Best available technology (as in benchmark installation)	94%	0.72	€/ton product	0.5
Direct use of N_2O as anesthetic gas in medicine and as unreactive propellant in food industry	Reduced N_2O application	20-34%	0	€/person	0
	Further N_2O reduction in combination with other (liquid) anesthetics	53-68%	0	€/person	0
	Replace N_2O with alternative: e.g., Xe	100%	12	€/person	1700 – 9400
Wastewater treatment**	Process optimization to increase the N_2/N_2O ratio in effluent gases	40%	0	€/person	0
Fluidized Bed Combustion	Modifications (afterburner or air staging)	80%	0.08	€/GJ	16

*) Measures on farms are differentiated for rice/other crops, between manure and mineral fertilizer, and by farm size (farm area), hence cost ranges are particularly large

**) Applicable to centrally collected wastewater only of 1 €/kg N and an interest rate of 4% on fixed capital investments. Effects on investments also differ by farm size, with large farms being able to invest more cost-efficiently. Hence, in GAINS we differentiate costs by large (>150 ha), medium (30-150 ha) and small (<30 ha) farm area. Consistent with information on the respective technologies in the underlying literature, which report on fertilizer or emission reductions at constant yield, yield loss is not considered.

Emission reduction technologies have already been adopted in parts of the world at varying degrees, or can be expected to be implemented in the future because of existing legislation. In the baseline development of emissions such implementation is taken into account and the additional abatement potential is measured from the baseline. For example, adipic acid production is subject to control in many world regions. This is also the case for nitric acid production in the European Union, where installations of catalytic or thermal reduction are in operation. In addition, reductions in N_2O use as an anesthetic have been implemented in countries with developed health systems. In agricultural soil emissions, the level of fertilizer application is known to strongly differ between world regions. FAO's extrapolated trends implicitly assume harmonization and improvement of nitrogen use efficiencies (Alexandratos and Bruinsma, 2012) – therefore we understand that "good housekeeping" measures of fertilizer saving have already been accounted for in the fertilizer projections. Accordingly, we regard the respective measures to be fully adopted in the baseline by 2030.

Some of the critical assumptions mentioned above point to possible limitations of the approach. We discuss the sensitivities of individual sectors to various factors (section 5) and of further restricting future emission trends (section 6). These factors include (i) fertilizer prices, especially considering fertilizer subsidies, (ii) future technological development which would enable further efficiency improvements beyond the "good housekeeping" measures, and (iii) the combined effects of N_2O and other reduction measures for GHG or air pollutant emissions which could have an impact on the overall efficiency of such measures.

In order to account for further unspecified elements of input variability, a semi-quantitative method to assess uncertainty was developed (see Supplementary Information, part 3). Briefly, this method determines categories of uncertainty for each sector and all input elements (emission factors, activity, abatement efficiencies, implementation potentials, cost data); provides a quantitative interpretation for each of the categories; and presents a consistent method for combining this information. This approach estimates the uncertainty range (upper and lower boundary) for each of the results presented. External information is also included to further constrain uncertainty associated with the notoriously variable release of N_2O from soils. Inverse modelling results (Bergamaschi et al., 2015) and the comparison of global concentration trends with emission estimates (Davidson and Kanter, 2014) imply that emission inventories perform better than previously expected (IPCC, 2006; Winiwarter and Muik, 2010).

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3. Results at the global scale

Results for N_2O emissions and emission projections derived in GAINS, with and without additional abatement technologies, are shown in Figure 1 by source sector. The dominant anthropogenic sources are fertilizer additions to agricultural soils (both mineral fertilizer and animal manure), manure management and wastewater treatment. Emissions from industrial processes were a major source in the past, and although they were reduced in many parts of the world before the year 2000, they remain unabated at many installations in other regions.

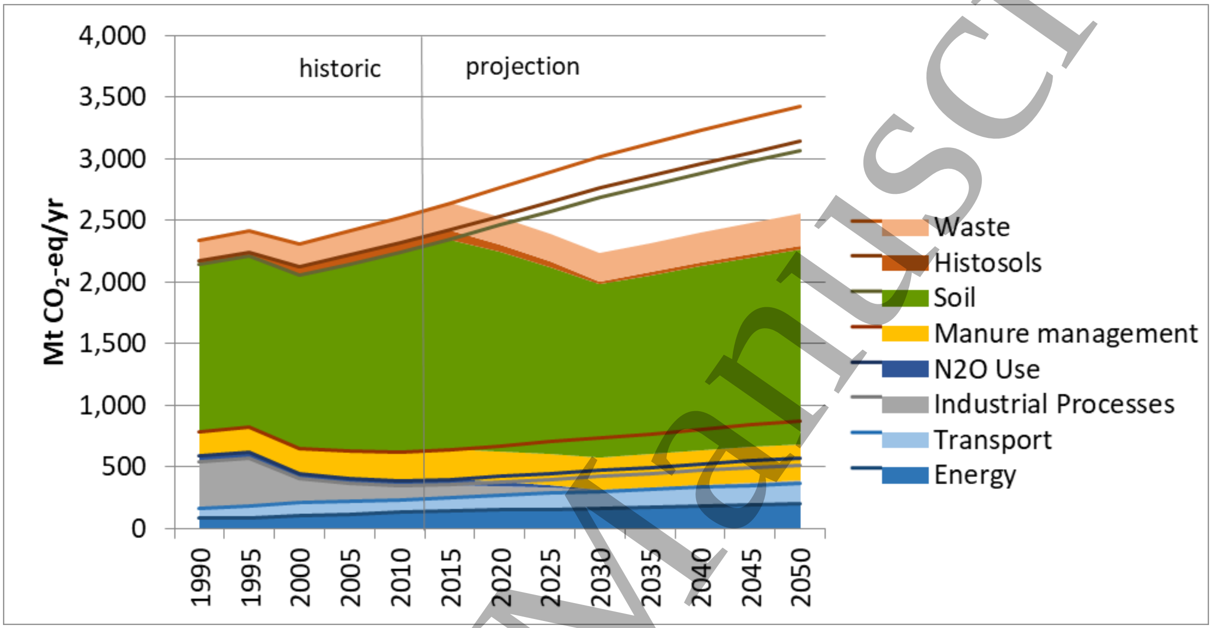

Fig. 1: GAINS global emission scenarios for N_2O stacked by source sector, such that the top reflects total emissions. The lines represent the baseline developments, the colored area the situation when all abatement technologies can be adopted. Developments are identical until 2015 and the baseline of the respective sector can be traced along the lines in darker shades of a similar color. A linear implementation rate has been assumed to display emission abatement between 2015 and 2030.

The GAINS estimates agree well with other studies, which have varying degrees of spatial and sector resolution (e.g., UNEP, 2013; Davidson and Kanter, 2014; Janssens-Maenhout et al., 2014). In addition, published information on the future development of these emissions largely support the findings presented here (UNEP, 2013; Bouwman et al., 2013; Bodirsky et al., 2012). A detailed analysis is provided in the Supplementary Information part 2.

FAO projections of the future development of agricultural activities (Alexandratos and Bruinsma, 2012) imply an increase in fertilizer consumption, which would in turn lead to a continuing rise in N_2O emissions until 2050. Other source sectors follow similar trends. Even if emission abatement measures are implemented to their maximum technically feasible extent, global emissions in 2050 are not expected to decrease below the 1990-2010 level.

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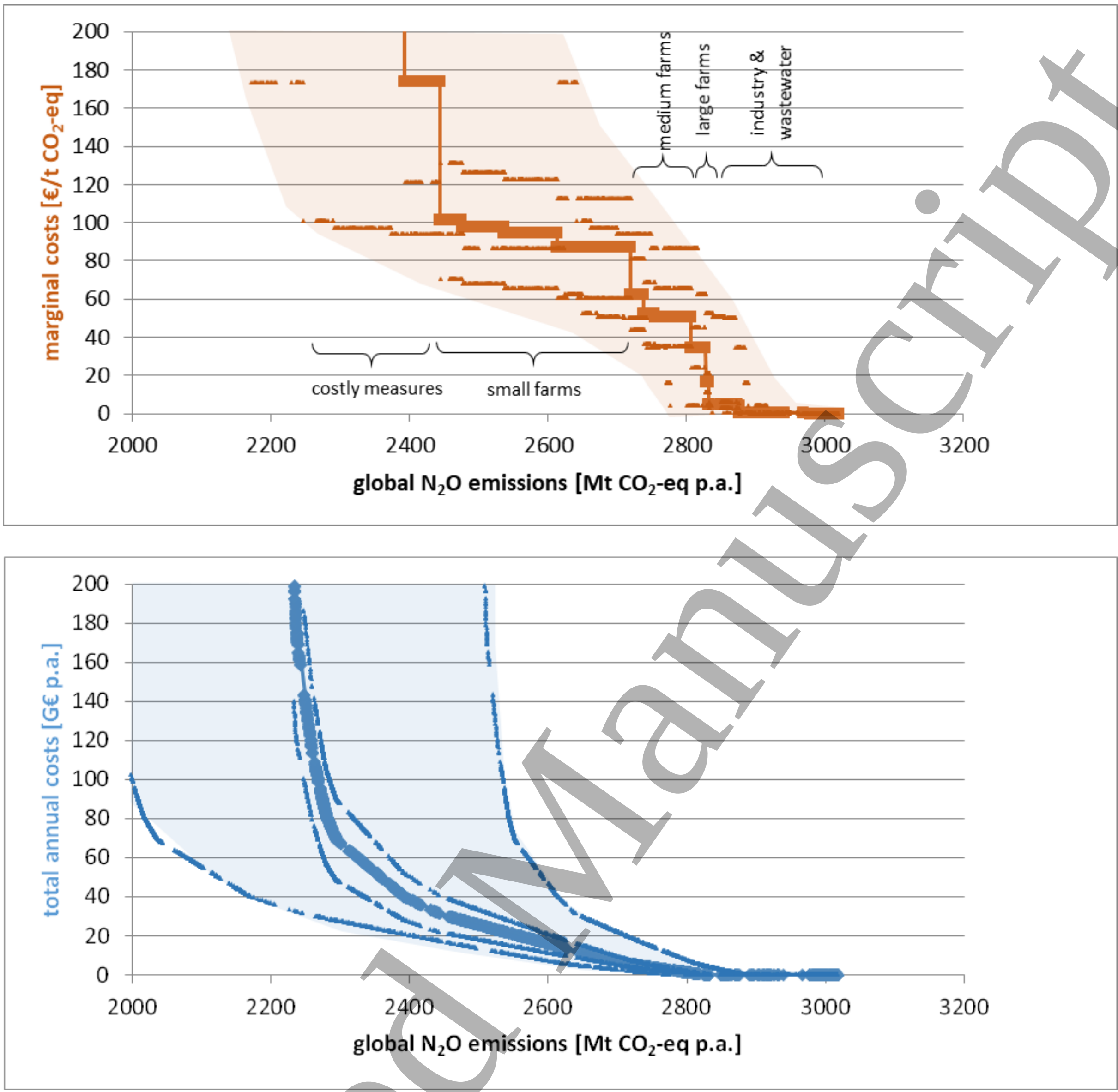

Fig. 2: Marginal and cumulative cost curve of global N_2O emission assessed for the year 2030, with respective uncertainty areas. Marginal costs (upper panel) represent the costs needed to decrease emissions starting from the projected baseline emissions – from right to left – using the abatement technologies listed in Table 1 (and presented in detail in the SI). Costs of all measures integrated yield the cumulative annual costs (G€ or billion €) shown in the lower panel.

Cost-efficient emission reductions prioritize abatement options with the least marginal costs. Sorting abatement measures by increasing marginal costs allows us to develop least-cost emission abatement curves. We compiled information on uncertainty in emission estimates, projections, implementation of measures and their costs into cost curves (shown in Figure 2 for the year 2030). The upper panel shows the marginal abatement costs per unit of reduced GHG emissions (converted to CO_2-equivalent using a Global Warming Potential of 298 for

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N_2O). The lower panel shows the estimated total annual cost level for attaining a given emission reduction level. These marginal abatement costs and total annual costs are presented with their respective uncertainty ranges on the global scale, demonstrating how varying assumptions of key parameters affect emissions, reduction potential and costs (see Supplementary Information, Table SI 6). Because the emission projection entails a strong deterministic element (not least expectations of future economic development) and is driven by the respective storyline, the projection is not included in the uncertainty analysis.

While the uncertainties remain substantial, a clear distinction between certain classes of measures remains. First of all, a considerable amount of emissions can be removed at zero or very low marginal costs (below 10 €/ton CO_2-eq), mostly by measures in industry, by reduced N_2O use as anesthetics, by optimized wastewater treatment (wherever secondary or tertiary treatment is available), and by agricultural measures (VRT) applied on large farms. This reduction potential is estimated at 6.2% (4.3% - 8.0%) of anthropogenic baseline N_2O emissions in 2030. The next class of measures is those available in agriculture (arable soils and manure handling) with marginal costs in the region of 30-100 €/t CO_2-eq for large and medium-sized farms, and 80-100 €/t CO_2-eq for small farms. Including all abatement measures mentioned extends the total estimated reduction potential to 18.0% (11.8% - 24.1%) of baseline emissions. Further abatement measures would allow the maximum feasible emission reductions of 26.0% (16.8% - 35.1%) to be achieved.

The resulting uncertainty of total costs remains small for small emission reductions, with 10% reductions estimated to be achievable at a global annual cost of 5.9 billion € (4.1 - 7.7 billion €). But the uncertainty range for costs increases rapidly as emission reductions grow. In part, this is due to a lack of practical experience (and hence higher uncertainties) associated with higher cost measures. It also may be a limitation of the semi-quantitative method used for uncertainty analysis, which cannot fully constrain results from independent datasets. That effect becomes relevant at more stringent controls, where the uncertainty margins provided may reflect an upper boundary and overstate the actual uncertainty.

4. Differentiation by source sector and world region

Economic structures, emission patterns and abatement potentials differ strongly between regions and countries. Figure 3 provides baseline emission projections by source sector for the year 2030 and for the 11 world regions defined for the MESSAGE model. Detailed shares are also shown in the Supplementary Information (Figure SI 7).

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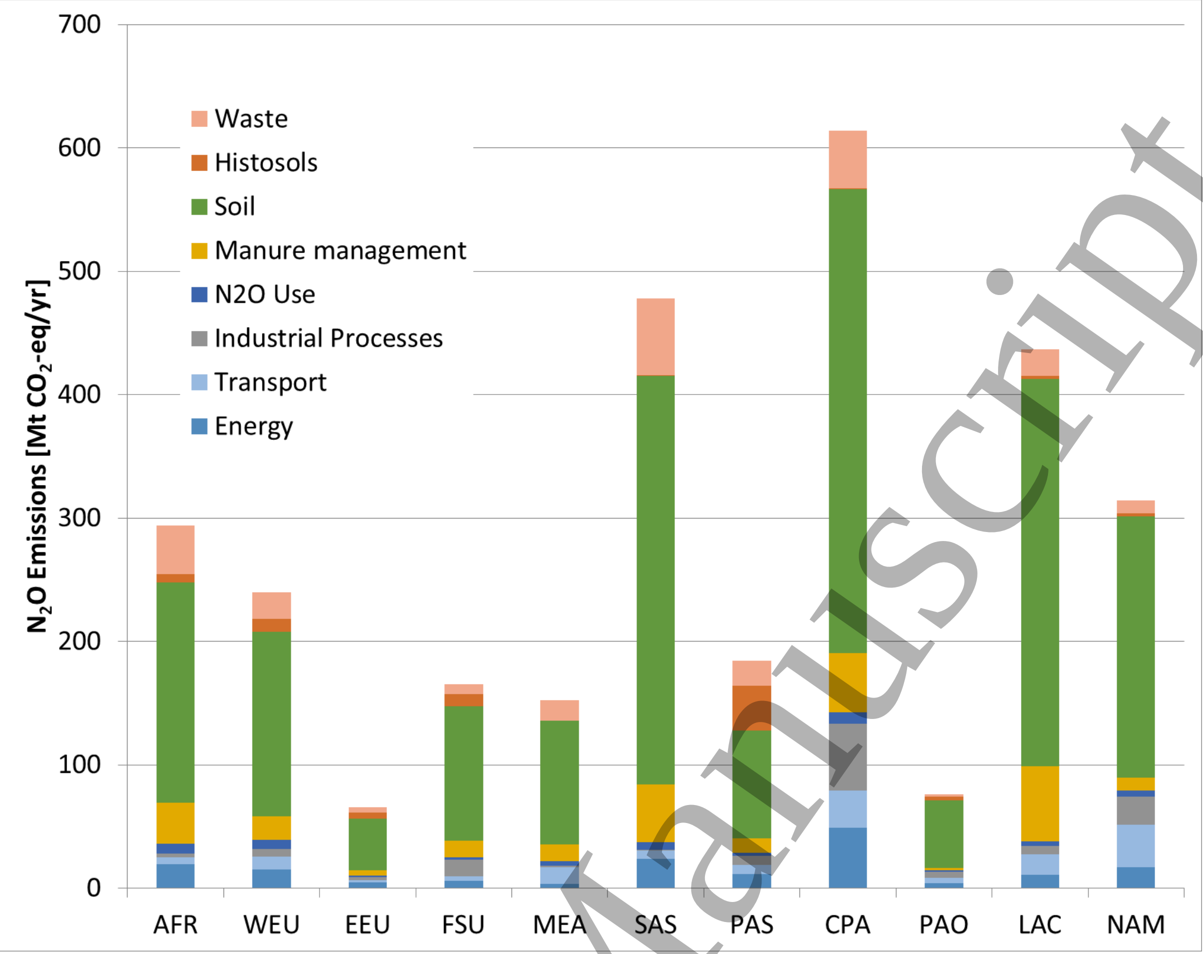

Fig. 3: GAINS sector split of regional N_2O emissions, 2030 baseline. World regions are defined as follows: AFR – Sub-Saharan Africa; WEU – Western Europe; EEU – Central and Eastern Europe; FSU – Former Soviet Union; MEA – Middle East and North Africa; SAS – South Asia; PAS – Other Pacific Asia; CPA – Centrally planned Asia and China; PAO – Pacific OECD (Japan, Australia, New Zealand); LAC – Latin America and the Caribbean; NAM – North America.

In all regions, the largest share of emissions comes from agricultural soils (including manure applied on soils) – typically 61-72%. Only in Other Pacific Asia is it much smaller than that (48%), as in this region other sectors are particularly high emitters. Emissions from agricultural soils are particularly large in those world regions that have intensive agriculture, in part triggered by high population numbers. Thus the absolute contributions from this source sector are the largest in Centrally Planned Asia (including China), South Asia and Latin America. Manure management emissions are roughly equally high between these three regions. The remaining differences in total emissions are then related to other emission sectors. Energy and industry emissions are high in Centrally Planned Asia, making this region the highest emitting region in absolute terms. Latin America has lower emissions from wastewater as a result of a smaller population, and hence also lower overall emissions than South Asia.

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Industry is an important source in Centrally Planned Asia, in the Pacific OECD countries, and in the Former Soviet Union. In these world regions, it constitutes the second largest sector at 7-9% of total emissions. In North America, transport emissions are higher (11%) but industry still contributes 7%. Industrial emissions are caused by the production of nitric acid, except in China, where about 90% of the emissions are attributed to adipic acid production—an industry that is equipped with abatement devices elsewhere. Other world regions either have much smaller industrial activity, or—as in Western Europe—all plants, including nitric acid production, operate with emission abatement already in place that is accounted for in the baseline.

Waste, specifically wastewater treatment, is the second largest sector in Africa, South Asia and in the Middle East, at shares between 11 and 13%. While the share is smaller for Western Europe (9%), it remains the second most important sector. In Pacific Asia (dominated by Indonesia, Malaysia, South Korea), the share is also 11%, with even higher emissions are attributed to the agricultural use of histosols – a soil type particularly rich in carbon that is prevalent in these countries.

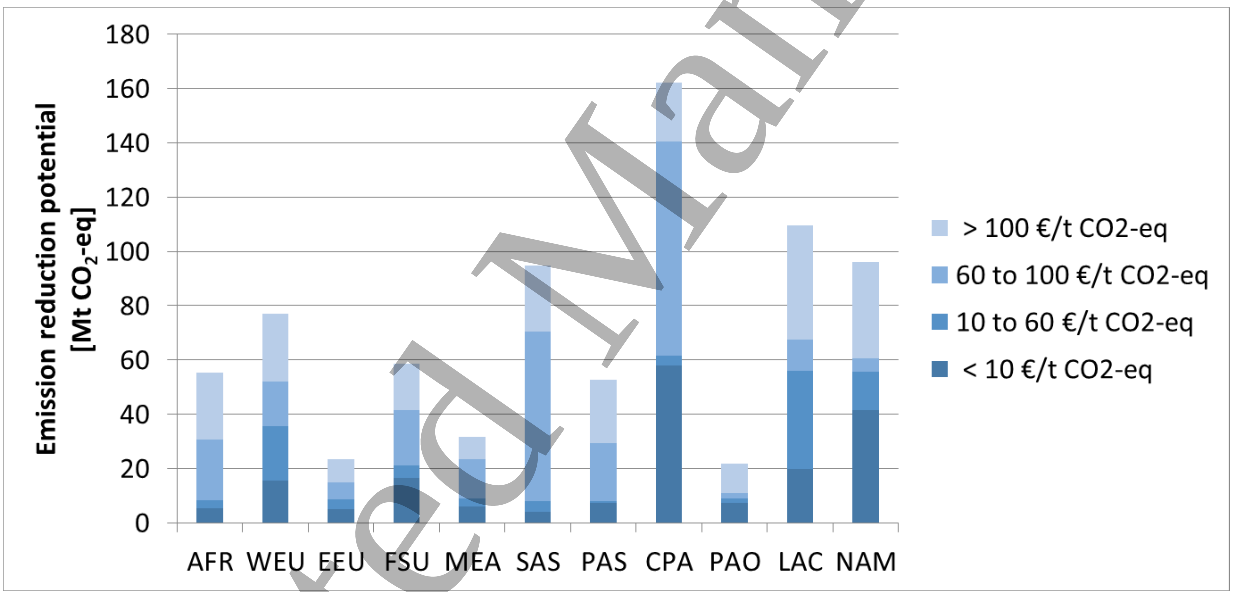

Fig. 4: Fraction of 2030 abatement potential in different cost classes by world region (see Fig. 3 for acronyms). The low-cost options (< 10 €/t CO_2-eq) cover the chemical industry, wastewater, simple options regarding direct N_2O use, and the most cost-effective measures on large farms; medium-cost options (10-60€/t CO_2-eq) include measures on large and medium-sized farms, while the high-cost options (60-100 €/t CO_2-eq) cover those on small farms (and some expensive options on other farm sizes). Very high costs (> 100 €/t CO_2-eq) are associated with expensive measures on small farms, on grazing, histosols, and on fully phasing out direct N_2O use.

The potential for reducing N_2O emissions in the respective regions is also strongly influenced by the respective contributions of source sectors. Figure 4 rates the emission reductions by

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their different marginal costs. The overall emission reduction potential (again shown for 2030 for consistency) is the largest where emissions are high, i.e. in Centrally Planned Asia (China), Latin America and South Asia. But the reduction potential is also high in North America, surpassing that of South Asia. Sectors that allow efficient emission reductions include industry and direct N_2O use, as available technology allows to remove a large proportion of emissions. For other sectors, only a fraction of their emissions can be reduced – and even that may depend on the circumstances. For instance, optimizing wastewater treatment, basically available without additional costs, is limited to situations where secondary or tertiary treatment is available. This limits the availability of this otherwise cost-effective measure in large parts of the world.

As the results presented in Fig. 4 show, Centrally Planned Asia has the largest emission reduction potential with costs below 10€/t CO_2-eq. Three quarters of this potential, totaling 58 Gt CO_2-eq, is due to the possibility of low-cost abatement in adipic acid production. North America also has a considerable potential in this cost range, at 42 Gt CO_2-eq. Again industry contributes, in this case nitric acid production, but about half of the potential is due to Variable Rate Technology in agriculture, which is considered fairly cost-efficient for the large farm sizes prevalent in this part of the world. In relative terms, large farm sizes lead to half of the abatement potential for Latin America and for Easter Europe as well, while for Pacific OECD and the Former Soviet Union, industry retains the larger abatement potential. No single factor can be identified for Western Europe, where all sectors contribute to the low-cost measures in a similar way.

The overall N_2O abatement potential is strongly determined by the availability of measures for reducing agricultural soil emissions, the largest source of emissions. As discussed above, a high share of large farms allows measures to be implemented at low costs. There are, however, also repercussions of farm sizes to the higher cost ranges. For example, the costs of VRT also determine the cost difference to the use of chemical inhibitors. When this difference increases (with VRT cheaply available on large farms), marginal costs for inhibitors become considerably higher. Hence, for North America, the considerable share of low-cost measures causes a large fraction of abatement in the high-cost range above 100 €/t CO_2-eq. In addition, high-cost measures make up a large fraction of the abatement in areas where histosols play an important role in total emissions. This specifically affects Pacific Asia, where more than half of the abatement attributed to the highest cost class is due to abandonment of the agricultural use of histosols.

5. Discussion and sensitivities

Understanding the robustness of model results is critical to an adequate interpretation. Here we discuss the sensitivity of sector-specific results and assess which conclusions are robust with respect to the input assumptions. Such an investigation of sensitivities is complementary to the evaluation of uncertainties provided above as it progresses from evaluating observed variability and specifically looks into possible reasons for variations.

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Representation of soil emissions: By far the largest share of emissions derives from agriculture, specifically from applying nitrogen (N) fertilizer to soil. This sector also contributes most strongly to the abatement potential. We note that available abatement options differ by sources of fertilizer application and by size class of farms, and we differentiate a series of such options of increasing stringency. In the baseline, however, a simple proportionality factor between fertilizer application and emissions is assumed (following IPCC, 2006). It is well known that emissions depend on a number of soil parameters (Bouwman et al., 2002), which cannot be accommodated in the simpler approach selected here. Differences in soil properties, vegetation, or weather impacts thus are not reflected. Ideally, soil models would be able to cover all such issues. The approach chosen by USEPA (2013) demonstrates that the application of soil models is in principle possible, even on the global scale. Still, so far such complex process-based models seem unable to perform accordingly (Leip et al., 2011). Thus an approach that at least agrees with national reporting guidelines according to IPCC (2006) seems to adequately represent the current state of the science.

Recent studies (Shcherbak et al., 2014; Gerber et al., 2016), baed on field measurements and modelling, have determined a non-linear relationship between emissions and fertilizer application, attributing higher emissions to excessive nitrogen application. Differences to the IPCC approach remain within typical uncertainties for most application rates – just the incremental effect of added (or reduced) fertilizer application is much greater, possibly twice as high compared to the linear approach. Hence, possible emission reductions in high-N areas might be much more efficient than otherwise expected, if application is significantly exceeding plant needs. Using 2030 FAO projections in our analysis we assume that globally nitrogen use efficiency has improved so that the situation of overfertilization will converge across a wide range of different situations – also limiting the effect on mitigation caused by the non-linear relationship. Likewise, introducing more fertilizer in low-N areas (Sub-Saharan Africa: see also Hickman et al., 2015) will have less effects on emissions than otherwise expected – at least as long as uniform conditions apply. Hutton et al. (2017) point out that for Tanzania only 10% of farms receive all the mineral fertilizer available – if we assume that additional fertilizer is not just distributed on all farms evenly, but just extends the share of farms receiving fertilizer, the non-linearity effect disappears. Appropriate allocation of fertilizer application in future scenarios thus will remain a challenge.

Effect of fertilizer prices and interest rates: Fertilizer savings (and thus fertilizer prices) are applied against investments and other cost factors in the cost estimates of the key low-cost agricultural measure of VRT. Hence assumptions regarding fertilizer prices are critical, as are the interest rates chosen for amortization of investments (machinery costs on large farms). These factors do not influence the costs of chemical inhibitors, which is assumed to directly affect the N_2O release rate but not fertilizer consumption.

We find that, at interest rates of 4%, part of agricultural emission abatement will be available at costs below 10 €/t CO_2-eq. For large farms (>150 ha) operating their own machinery, marginal costs of about 5 €/t CO_2-eq have been computed, with assumed fertilizer costs of 1 €/kg N. Variations in fertilizer prices (triggered in part by the cost of natural gas) of +/- 20% are well documented, and differences also occur between fertilizer types. At lower fertilizer

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prices, for example 80 cents/kg N for current (early 2017) urea prices, these savings will be smaller and costs will increase to almost 40€/t CO_2-eq. If fertilizer prices rise above 1.03 €/kg N this option becomes profitable even when emission reductions are ignored, as fertilizer is saved effectively. In fact this may contribute to increasing availability of VRT on the market and its gradual introduction starting with very large farms in different parts of the world. However, fertilizer savings alone have been described to be insufficient to trigger implementation of this technology (Auerbach, 2001).

If private interest rates of 10% are assumed (which also underlie our cost estimates for contractors operating on small and medium sized farms) costs increase to 50 €/t CO_2-eq. If a lower fertilizer price then diminishes savings and overall costs increase, the more stringent option of applying inhibitors may become more cost efficient, as it is independent of investment or fertilizer price. This is the case at around 45, 55 and 95 €/t CO_2-eq for large, medium and small farm sizes, respectively.

Globally, the low-cost agricultural abatement potential that can be affected by fertilizer prices and interest rates amount to 42 Mt CO_2-eq (1.4% of 2030 emissions, much less than industry but larger than wastewater). This potential will move into a higher cost category when considering higher interest rates or lower fertilizer prices.

Effect of fertilizer subsidies: The costs of emission reductions are higher on small farms which dominate in Asia, including China and India. A total reduction potential of 243 Mt CO_2-eq is estimated for small farms at costs of up to 100 €/t CO_2-eq. In general (and in all analyses presented here) GAINS does not consider the effects of fertilizer subsidies, therefore it is instructive to understand the effects such subsidies might have. While China has been active in removing or phasing out these subsidies, in India the maximum retail price for urea has been set at a value of about a quarter of the current world market price, around 20 cents per kg of N. At such prices, fertilizer saving is less important to farmers, and these savings also do not compensate costs involved in VRT. As shown above, inhibitors will become the cost-efficient option in such a situation, as they will be available at only slightly higher marginal costs. The difference in marginal costs is most striking for the large farms, but large farms play a minor role in the regions of concern. Assuming subsidies are used in all countries of the African and Asian regions and affect large farms, the abatement potential merely decreases by 1 Mt CO_2-eq in the cost range below 50 €/t CO_2-eq. At higher marginal costs inhibitors start to be preferred on large farms. Hence any effect of fertilizer subsidies remains negligible to this analysis.

Fertilizer life cycle: Fertilizer savings provide an additional impact on GHG emissions via the production side which is not accounted for in the standard GAINS analysis. Compiling several life cycle assessment studies based mostly on European plants, Wood and Cowie (2004) provide information for different fertilizer types. According to their results, roughly 2 kg CO_2 are emitted for each kg N fixed during ammonia production, and additionally 2kg CO_2-eq of N_2O emissions are emitted for fertilizer nitrates during nitric acid production (plants with abatement installed, but standard of 2004). Ammonia production via coal, the more typical pathway in China, is less efficient and more carbon intensive than the process based on natural gas. GHG emissions may thus be roughly estimated at 6 kg CO_2-eq per kg N

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for China (urea), 4 kg CO_2-eq per kg N for Europe (ammonium nitrate), and 2 kg CO_2-eq per kg N in North America (anhydrous ammonia). Although smaller, this is similar to the total N_2O soil emission factor from mineral fertilizer application (direct and indirect) of 2% used in GAINS, which converts to 9.4 kg CO_2-eq per kg N. If these further effects of reducing fertilizer inputs are also factored in, costs of Variable Rate Technology per unit of GHG saved would decrease accordingly by between 15 and 40%.

Industry: In addition to soils, the chemical industry is a key sector that offers considerable abatement potential for N_2O emissions, especially in industrialized countries. Technical devices are commercially available that can even be retrofitted to existing installations of nitric acid and adipic acid plants, and are generally applicable. Examples of successful abatement exist, with a voluntary agreement of adipic acid manufacturers globally forged in the late 1990s, and with the EU's emission trading scheme, which enabled a decrease in N_2O emissions by a factor of four between 2007 and 2012 (EEA, 2014). Further abatement is possible where these measures have not yet been implemented, as is the case in the majority of nitric acid plants outside Europe, and some selected new adipic acid plants. Following Schneider et al. (2010) we assume that adipic acid plants (four individual installations) in China started production during the 2000s without abatement in place. If data are correct (which technically could be easily monitored at site) that offers opportunity for significant and cost-effective (below 1 €/t CO_2-eq) abatement. An official Chinese inventory (PRC, 2016) indicates N_2O emissions from chemical industry are almost twice as high as those presented here (76 Mt CO_2-eq for 2012, while GAINS estimates 42 Mt CO_2-eq for 2015) but provides no attribution to a specific industry. This implies that our assumption that only some adipic acid plants operate without abatement devices may be overstating actual control. Similarly, emission reduction in nitric acid (and caprolactam) production offers significant reduction potential in North America and Eastern Europe. Extended abatement technology is available for both industries in addition, but as the initial thermal/catalytic reduction already removes 80-95%, the major part of abatement is in this initial technology. Marginal costs for the extended technology still remain in the low-cost set below 10 €/t CO_2-eq. Total emission reductions expected from low-cost industrial production devices is 104 Mt CO_2-eq per year (3.5% of global baseline emissions estimated for 2030), more than 40% of which are assigned to the four individual adipic acid plants in China mentioned above and assumed to currently operate unabated.

As costs of technical measures in industry also account for investments, overall results depend on the interest rate assumed. Here it is important to note that, independent of the interest rate chosen, the cost level remains less than 10 €/t CO_2-eq.

Wastewater: Opportunities to reduce emissions in the wastewater sector are assumed to be achievable as modifications within normal operations and without additional costs. Wherever secondary or tertiary treatment of wastewater is provided, optimizing strategies to reduce emissions are available (e.g., proper selection of microbial communities performing denitrification). The global emission reduction potential from this sector, estimated at 25 Mt CO_2-eq for 2030, is less than 1% of global N_2O emissions. Most of these reductions can be implemented in developed countries that have advanced wastewater systems in place. There is considerable need, for sanitary reasons and in terms of water quality, to extend the share of

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treated wastewater in all countries. Constructing wastewater plants is expensive, and as its primary purpose is not to reduce GHG emissions, it is not included as a specific N_2O mitigation option in the analysis. If we assume, however, that improved wastewater treatment (at least secondary treatment) were made available wherever wastewater is centrally collected (in general in most urban areas), the reduction potential would increase from 25 to 29 Mt CO_2-eq.

Considering co-benefits: Specific regional circumstances may affect our conclusions. In areas where nitrogen use efficiency needs improvement for other reasons (Zhang et al., 2015), like for air pollution control (Wu et al., 2016), measures that limit N_2O at the same time will become efficient on small economic units as well. Likewise, construction of wastewater treatment to improve water quality will improve the potential of emission abatement in that sector. A full analysis of such interrelations may take advantage of the results presented here, but is beyond the scope of this paper.

6. Pathways to enhance emission reductions

As shown above, currently available technology could reduce global N_2O emissions by about 26% below the baseline projection in 2030. Given the expected growth in world population, energy use und industrial production, these emission reductions would not be sufficient to balance the anticipated increase in baseline N_2O emissions compared to 2010, even in the maximum abatement case. Further efforts will be needed to comply with the challenge to phase out global GHG emissions. Several paths could be taken:

Refinements of existing options: There are many countries where fertilizer reduction/increase of nitrogen use efficiency has not yet happened, and the underlying assumption taken here that good housekeeping options can be considered as part of the fertilizer consumption baseline is incorrect. Indeed, Lassaletta et al. (2014) provide 50 year trends of fertilizer use by country, and identify several important countries (including Australia, China, India) that have not seen a step improvement in their nitrogen use efficiency. On the other hand, it could also be argued that there are regions where fertilizer application is so low that further reductions are feasible only to a limited extent. Again, Lassaletta and colleagues provide a list of countries where they assume “soil mining” takes place (several African countries, but also Argentina and the countries of the Former Soviet Union), a process depleting soil N and jeopardizing soil fertility in the long term. However, quantifying the effects of such varied input assumptions shows only limited impact on the global reduction potential. For instance, in 2030, the global reduction potential increases from 26.0 to 27.2% when allowing further improvement of nitrogen use efficiency for the set of countries that have not seen such improvements in the past; and decreases to 25.9% when at the same time limiting emission reductions in countries that suffer from soil nitrogen depletion to half of their nitrogen input.

Increasing the efficiency of measures: The scientific literature has argued for a general need to improve nitrogen use efficiency in agriculture (Roy et al., 2002; Zhang et al., 2013; Oenema et al., 2013). Implementation needs to take advantage of specific action: Winiwarter et al. (2014) discuss more speculative abatement which may be available in the long run –

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even if possibly at immense energy costs. If we allow the emission reduction measures implemented in GAINS to increase in their efficiency by 1% per year as a result of technological development, baseline emissions would be about 10% lower in 2030 and 26% lower in 2050. This would also open new scope for additional emission reductions, but possibly also sacrifice part of the yields (which so far have been assumed unchanged by measures taken) and in consequence also require more elaborate economic evaluations. Compared to the baseline, a maximum of 39% of emissions could then be reduced in 2030, and 61% in 2050. This means that even under such idealized conditions 73% of the 2010 N_2O emissions would remain in 2030, and in 2050 a reduction to just over half of the 2010 level (53%) is possible using highly efficient emission reduction technology, providing a notable change from the baseline assumptions.

Changing human diets: Structural changes like changing human diets to lower consumption of animal protein would decrease agricultural production and hence nitrogen (and N_2O) emissions. Any change in consumer preferences will take time and adopting policies may also require other reasons than GHG reductions: Typically, the relevant scientific literature argues that low animal protein diets are particularly healthy (Stehfest et al., 2009; Westhoek et al., 2015; Tilman and Clarke, 2014). Abatement opportunities exist, but are difficult to quantify as rebound effects like alternative agricultural use of the land gained may lessen the improvements. Oenema et al. (2013) estimate a total reduction potential for N_2O emissions from agriculture including human diet changes of up to 60% in 2050, adding about half to the reductions available from technical measures alone (41% reductions). Considering the overall requirement of emission reductions and the fact that technical measures will not suffice, exploring diet changes further will be essential even if this disrupts the purely economic approaches of agricultural industry. Similar to diet changes, also avoiding food wastage may reduce the need of agricultural production and its N_2O emissions – only that the reduction potential of this option will remain quite limited for an assumed wastage rate of 30% or less (Parfitt et al., 2010), which can be tackled only in part.

7. Conclusions

Anthropogenic emissions of N_2O are, next to CO_2 and methane, the third most important GHG contribution to global warming. Efforts to decrease GHG emissions thus also need to include N_2O. In the short term, reductions of N_2O emissions must rely on the adoption of existing technologies. The results presented here, which specifically match technologies to the respective source sectors, show that full implementation could halt further emission increases, but would be insufficient to reduce global emissions in a growing world economy.

Our detailed analysis of the marginal abatement costs of N_2O emission reductions identified key elements of effective abatement strategies. Low-cost options are available in the chemical industry, for secondary and tertiary wastewater treatment systems, and to some extent in agriculture, especially for large farms. The extent of the agricultural measures covered in the low cost range may be affected by fertilizer prices and interest rates. The cheap options basically concern industrialized countries including China and large economic units (bulk industry, large farms) and about 6 +/- 2% of global emissions in 2030.

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In contrast, many of the mitigation options prevailing in developing countries are quite costly, at or even exceeding 100 €/ton CO_2-eq. Only if options are successfully implemented for large-scale agriculture and with technology becoming available more generally and at lower prices, can smaller farms be addressed.

Efforts to scrutinize the results presented (validation and uncertainty analysis) allow for identifying areas that are generally better understood upon which reasonably robust policy decisions can be based. This includes the low-cost options and areas/sectors in which expected future development is less dynamic. At the same time, the approach points out areas where further information may be needed or even become decisive. One such element is to perform rather simple stack measurements on a few individual industrial plants that emit at a level of global relevance. Further focus will also be needed on sources that may exhibit significant growth – specifically fertilizer application in parts of the world where soil is deprived of nutrients, like Africa. This includes efforts to understand where application actually takes place, so that also effects of non-linearity of N_2O emissions vs. fertilizer application can be taken into account properly.

Hence, the results of this study help devise ways to bring down emissions of N_2O by: (i) implementing available measures to reduce emissions to at least stabilize global emissions, (ii) searching for improvements to such options by way of technology development, and (iii) looking into options beyond the technical realm such as a change in human diet, which is seen as necessary to further cut emissions.

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