Reducing nitrous oxide emissions from agriculture: review on options and costs

Wilfried Winiwarter, IIASA
Sajeev Erangu Purath Mohankumar, University of Graz

International Institute for Applied Systems Analysis, Laxenburg, Austria

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1. Introduction

Agricultural emissions of nitrous oxide (N_2O) may be categorized into three main categories: emissions from manure management, emissions from agricultural operations on carbon-rich soils (histosols), and the direct and indirect emissions as a consequence of nitrogen addition to soils. In this paper, we only focus on the latter, which in 2012 covered 84% of the EU's agricultural N_2O emissions or 67% of the total N_2O emissions (EEA, 2014). All options presented will thus refer to this very considerable share of emissions.

Emissions due to adding nitrogen to soils are the result of microbial soil activities. N_2O is released as a side product of nitrification and denitrification. Once formed in the deeper soil layers and emanating towards the surface, it may itself be removed by further denitrification. With each of these stages affected by a number of environmental parameters (temperature, soil water content, soil aeration, soil pH, nitrogen content and chemical form, carbon content, etc.), the release of N_2O from soils tends to be highly variable in space and time, and thus its quantification is uncertain. Recognizing these difficulties, the methodology developed as the default "Tier 1" approach by IPCC (IPCC, 1997; IPCC, 2006) to assess N_2O emissions, which basically assumes soil emissions being proportional to input of reactive nitrogen (Nr), is associated with an uncertainty range of an order of magnitude (IPCC, 2006). Nevertheless, this method (IPCC, 1997) has been used by EU member countries for their annual greenhouse gas (GHG) inventories. When comparing these inventories with inverse modelling results (emission estimates based on atmospheric N_2O measurements and dispersion models only), agreement was much better than expected at 30% or much smaller difference, depending on the approach taken (Corazza et al., 2011; Bergamaschi et al., 2015). It has been argued (Leip et al., 2011) that highly variable results available from field studies largely cover all possible situations rather than describing the uncertainty, such that the methodology can be confirmed to be useful.

Strictly following the default option of the IPCC guidelines, emissions are simply proportional to the amount of Nr added to soil, in whatever form. Consequently, the only fully compatible possibility to reduce emissions is to decrease this addition. While fertilizing is an essential prerequisite to industrial agriculture, there are many reasons to optimize the amount applied. Adding Nr nutrients not only negatively affects climate, air, water, soil and biodiversity, but fertilizer is also a major cost factor in agriculture. Therefore, appropriate management of nutrients is also in the core economic interest of the sector.

For N_2O, the GAINS model (Winiwarter, 2005; Höglund-Isaksson et al., 2013) uses projections of the amounts of Nr applied according to external information sources. Emissions are calculated by using default emission rates and explicitly defined measures to abate soil N_2O emissions. Even as the N_2O-related measures have been lumped into archetypical groups, a focus remained on pinpointing specifically the respective actions taken. These measures again address the amount of Nr applied, and their explicit coverage allows distinguishing measures to reduce emissions that have been implemented from those that have not.

The purpose of this report is to review the available scientific literature with regard to technical options available for the reduction of N_2O emissions, in order to update and extend the existing implementation in GAINS (see Winiwarter, 2005; Höglund-Isaksson et al., 2013). The focus of this work is again on possible emission reduction in the EU for the year 2030.

The report has the following structure. Section 2 summarizes the evidence on effective emission abatement technologies: fertilizer reduction, fertilizer timing, variable rate technology, and on enhanced efficiency fertilizers including the use of nitrification inhibitors. Section 3 provides information on measures for which evidence was not sufficient to be recommended for use in GAINS, as selecting specific fertilizer type, introducing no-till strategies, or crop rotations. Section 4 discusses uncertainties while section 5 summarizes the changes applied to the GAINS methodology in order to better reflect the recent literature.

2. Technical options to effectively reduce N_2O emissions

Defining abatement options in GAINS explicitly requires continuous updates and adding mitigation measures when new knowledge and scientific evidence is collected. While little additional information can be expected for the well-established options (“fertilizer reduction” and “fertilizer timing”, see below), study of recent scientific literature helps to establish a better understanding of further abatement that is or is expected to become available in the foreseeable future. Here we focus on options that can be implemented by 2030, and which are expected to provide a potential for emission reductions.

2.1 Fertilizer reduction

GAINS considers an option of simple housekeeping options (maintenance of spreader, minimize losses beyond edges of fields, etc.) to reduce fertilizer application (Winiwarter, 2005; Höglund-Isaksson et al., 2013). Mineral fertilizer is a major cost factor in agriculture. There is an economic advantage of improved use of Nr, or increased nitrogen use efficiency, which in turn triggers the reduction of emissions. Under such conditions certain improvements will occur autonomously when driven by an external advantage – in the case of fertilizer use, cost savings clearly are a reason to decrease emissions. Improved nitrogen use efficiency can be demonstrated for a number of European countries (OECD, 2008) in the past, and further improvements of the relationship between nitrogen collected in crops and nitrogen input have been assumed for the future by the CAPRI model as used by GAINS as the external source of information on agricultural trends. Fertilizer projections thus implicitly cover to some degree similar reductions as expected in the measures implemented in GAINS. To avoid double counting we assume the low-cost GAINS option “fertilizer reduction” implemented in the past to be *de facto* covered by the CAPRI projection of improved nitrogen use efficiency as used in the Reference 2013 scenario for 2030 (Capros et al., 2013).

2.2 Fertilizer timing

As a next stage to minimize fertilizer need, GAINS considers options that would allow to supply nutrients to plants when needed. This "fertilizer timing" options includes the use of catch crops or increased frequency of slurry spreading as well as a spreading ban during off-season (Winiwarter, 2005; Höglund-Isaksson et al., 2013).

New information is now available on further measures of timing and placement of fertilizer, which provides a mixed signal (Table 1). While the studies consulted by Bouwman et al. (2001) indicate plausible reductions of emissions when focusing on ways to apply fertilizer towards the plant rather than towards soil only, this is not generally the case. Specific experiments in the U.S. Midwest indicate cases when fertilizing rather late in the season, commensurate with plant requirements, still cause an increase in emissions. Interestingly, according to Liu et al. (2006), also deep fertilizer placement (fertilizer is applied about 10 cm below the surface) seemed to decrease emissions of N_2O without changing fertilization rates – indicating the emission factor to decrease.

Again, considering the inhomogeneities of the experimental data, but also the discrepancy between the review of available measurements on the one hand and the individual studies on the other hand it seems not plausible to draw specific conclusions on the abatement by these new data.

The relevance of proper timing clearly is not challenged from the results found during this literature review. Thus, fertilizer timing is maintained as an option of considerable reduction potential, in the form of its implementation in GAINS in 2013 (see Höglund-Isaksson et al., 2013, p. 61). Emission reductions derive from decreased fertilizer need, not from a change in emission factor, and are fully applicable under the IPCC methodology of a uniform emission factor.

Table 1: Results of additional options of varying timing and placement of fertilizer

Mitigation measure	***Scope***	***Crop***	***change in N_2O emissions (% from default)***	***Source***
Switch from broadcast to incorporated	Various locations around the world	Various Crops	-4	Bouwman et al. (2001)
Switch from broadcast to application in solution			-18	
Switch from single app to split scheme			-25	
Switch to side-dress from pre-emergence	Indiana, USA	Corn	28	Burzaco et al. (2013)
Switch to deep placement of fertilizer from shallow placement	Colorado, USA	Continuous Corn	-56	Liu et al. (2006)
AVERAGE			*-15*	

2.3 Variable Rate Technology

With fertilizer as a major cost factor in agricultural production, there is an incentive to not only provide temporally but also spatially adequate nutrient supply. As a subset of "precision farming", tools have become available that allow to use sensor technology and devices that distribute fertilizers accordingly (at "variable rates"). Like fertilizer timing options, variable rate technology (VRT) reduces fertilizer input. Scientific studies aim to collect information on yield impacts of reduced inputs, while at the same time assessing GHG emissions (Table 2).

Table 2: Effects of spatially optimized fertilizer application (variable rate technology) on fertilizer demand

Mitigation measure	*Scope*	*Crop*	*Fertilizer application (change from default) in %*	*Cost ($/ton N applied)*	*Source*
In-season canopy reflectance sensing	Missouri, USA	Corn	-36	NA	Roberts et al. (2010)
In-season canopy reflectance sensing	Missouri, USA	Corn	-28	NA	Kitchen et al. (2010)
Economic optimization methods to determine EONR	Missouri, USA	Corn	-21	NA	Hong et al. (2007)
Sensor based nitrogen calculator	Oklahoma, USA	Winter Wheat	-27	NA	Butchee et al. (2011)
Ultrasonic sensors to inform site specific management	Florida, USA	Citrus	-40	NA	Schumann et al. (2010)
Remote sensing to delineate zones	North Dakota, USA	Sugar Beet	-35	NA	Seelan et al. (2003)
Site specific management using aerial imagery, GIS and farmer perspective	North Eastern Colorado, USA	Corn	-18	50 to 70	Koch et al. (2004)
Crop reflectance sensor	Missouri, USA	Corn	-8	36 to 45	Scharf et al. (2011)
Site specific management using soil sampling, yield maps, chlorophyll meters and leaf color charts	Various Locations	Various Crops	-16	NA	Dobermann et al. (2004)
GreenSeeker™ technology	Various Locations	Various Crops	-15	Variable	ICF (2013)
AVERAGE			***-24***	***40 to 60***	

Reported costs include annualized investment (considering 10 years useful life) and application costs, while fertilizer savings are not accounted for.

This overview on available studies, first of all, shows a very consistent decrease of fertilizer application. These studies (comprising very different numbers of individual trials) suggest that on average about a quarter of fertilizer was saved. Where costs were available, these indicated to be rather low compared to the benefit of saved fertilizer. Costs are considered to consist rather equally of equipment investment and the actual application costs (Koch et al., 2004). With fertilizer costs in the order of 1 $ per kg (at 200 kg/ha, about one quarter reduction, this amounts to 50$ per ha), savings are in the same range as costs, but were not considered in the further treatment of this option.

Understanding that variability is considerable, that possible yield increases are not even discussed here and that N_2O emission reductions may be different from the decreases in fertilizer application (Sehy et al., 2003, argue their observed 17% less fertilizer could be translated into 34% reduction of N_2O), we simply use the non-weighted average of 24% fertilizer reduction as emission removal. Any cost estimate will be an exaggeration as long as not covering savings, too, thus we select the lower end of the range (40 $/t N) which translates into 33 €/t N applied using an exchange rate of $1.2/€ (consistent with historical average and consistent with PRIMES projections for 2030 for the new 2015 reference scenario).

Using precision farming techniques to reduce GHG emissions seems not to be a priority issue in Europe. Some publications, on a more general level, provide information on situations at which precision farming may become profitable (Diacono et al., 2012; Auernhammer, 2001). In the U.S., there have been more widespread activities to address VRT for which there is even at least one representation on the market already (GreenSeekerTM) – which can be seen as a result of the much larger farm sizes. We assume investments might also be shared by farmers in Europe, e.g. by a contractor model, such that the sparse cost information can be used here.

2.4 Enhanced efficiency fertilizers and nitrification inhibitors

Ongoing research attempts to further optimize timing at which Nr is being made available to the plant. As plants need nutrients continuously throughout the growing season, while any individual application operation is time-consuming and costly, fertilizers have been developed that are able to “lock” Nr for a limited time period. This limits the accessibility of Nr to weed crops as well as to leaching/gasification processes and thus improves efficiency. While efficiency improvements can be translated in reduced fertilizer demand, the experiments described basically compare N_2O emissions of plots receiving the same amount of Nr.

Enhanced efficiency fertilizers employ different principles. One may distinguish slow release fertilizers (SRF), which consist of components that require a microbial degradation stage before becoming plant available. Controlled release fertilizers (CRF) are fertilizers pellets that have an impermeable coating, which needs weathering (including microbial processes) for nutrients to get accessible. Finally, stabilized fertilizers contain inhibitors, chemicals that slow down or stop certain microbial processes. Important are Urease Inhibitors (UI) preventing the conversion of urea to ammonium, and Nitrification Inhibitors (NI) that limit oxidation of ammonia to nitrate. Inhibitors can be applied separately from fertilizers, but products are on the market that contain both fertilizer and inhibitors and allow application in a single operation. In soil, inhibitors are assumed to decay completely within a few weeks to months and thus will not have any persistent effect.

Table 3: Enhanced efficiency fertilizers and observed N_2O emission changes

(controlled release fertilizers are designated by gray shaded background, slow release fertilizer by orange shading; stabilized fertilizers do not have a background color)

Fertilizer	*Location*	*Period of Data*	*Crop*	*Tillage*	*Fertilizer app type*	*change in N2O emissions (% from untreated)*	*Source*
Polymer Coated Urea	Northeastern Colorado near Fort Collins, USA	7 years	Continuous Corn	NT	Band application	-41	A, B, D, E
		2 years	Continuous Corn	NT	Sub surface band application	-21	D
		4 years	Continuous Corn	ST	Band application	-40	C, E
		2 years	Continuous Corn	ST	Sub surface band application	-33	D
		2 years	Continuous Corn	CT	Band application	0	A
		1 year (90 days)	Spring Barley	NA	Sub surface band application	-71	G
	Bowling Green, Kentucky (silt loam)	2 years	Continuous Corn	NT	Surface broadcast	44	K
	Colorado, USA (clay soil)	1 year	Barley		Sub surface band application	-16	L
	Koriyama, Japan (loamy soil)	1 year	Corn		Sub surface band application	-68	L
	NA	NA	NA	NA	NA	-39	
Duration III	Northeastern Colorado near Fort Collins, USA	2 years	Continuous Corn	NT	Band application	-31	B
Polymer Coated Calcium Nitrate	NA	NA	NA	NA	NA	-16	N
Polymer Coated Ammonium Nitrate	NA	NA	NA	NA	NA	-86	
Super U	Northeastern Colorado near Fort Collins, USA	1 year	Barley (Corn-Barley rotation)	NT	Band application	-18	A
		1 year	Bean (Corn-Bean rotation)	NT	Band application	-42	A
		1 year	Corn (Corn-Barley rotation)	NT	Band application	-51	A
		1 year	Corn (Corn-Bean rotation)	NT	Band application	-54	A

		5 and 4 years	Continuous Corn	NT	Band application	-50	B, E, D
		4 and 2 years	Continuous Corn	ST	Band application	-48	C, E
		1 year	Continuous Corn	CT	Band application	-43	E
	Bowling Green, Kentucky (silt loam)	2 years	Continuous Corn	NT	Surface broadcast	-48	K
UAN + Agrotain Plus	Northeastern Colorado near Fort Collins, USA	4 years	Continuous Corn	NT	Band application	-36	B,D
		2 years	Continuous Corn	ST	Band application	-50	B,D
	Bowling Green, Kentucky (silt loam)	2 years	Continuous Corn	NT	Surface broadcast	3	K
UAN + N fusion	Northeastern Colorado near Fort Collins, USA	2 years	Continuous Corn	ST	Band application	-28	C
Neem + Urea	NA	NA	NA	NA	NA	-17	N
Urea + Nitrapyrin	Iowa	30 days	Soil only	NA	NA	-96	H
	Northeastern Colorado near Fort Collins, USA	2 years (100 days)	Corn	CT	Sub surface band application	-57	I
	NA	NA	NA	NA	NA	-48	N
Nitrapyrin + Ammonium Sulfate	Iowa	30 days	Soil only	NA	NA	-93	H
	NA	NA	NA	NA	NA	-11	N
Anhydrous Ammonia (AA) + Nitrapyrin	NA	NA	NA	NA	NA	-53	N
Urea + Encapsulated Calcium Carbide	Northeastern Colorado near Fort Collins, USA	2 years (100 days)	Corn	CT	Sub surface band application	-68	I
	NA	NA	NA	NA	NA	-52	N
DCD (dicyandiamide) + Urea	Iowa	1 year (90 days)	Spring Barley	NA	Sub surface band application	-37	G
	Colorado, USA (clay soil)	1 year	Barley		Sub surface band application	-37	L
	NA	NA	NA	NA	NA	-60	N
DCD + Ammonium Sulfate	Drained sandy loam soils (Greenhouse)	1 year (64 days)	Pasture Grass	NA	NA	-92	
	NA	NA	NA	NA	NA	-29	N
DCD + Liquid Manure	NA	14 days	Pasture Grass			-69	
	NA	NA	NA	NA	NA	-36	N
DCD + Ammonium Nitrate	NA	NA	NA	NA	NA	-33	N
DCD + Ammonium Sulfate Nitrate	NA	NA	NA	NA	NA	-26	N

DCD + Calicum Ammonium Nitrate	NA	NA	NA	NA	NA	-42	N
DCD + Potassium Nitrate	NA	NA	NA	NA	NA	-10	N
3,4-dimethyl pyrazole phosphate (DMPP) +	NA	3 years	Spring Barley, Corn and Winter Wheat			-51	
Ammonium Sulfate Nitrate (ASN)	NA	NA	NA	NA	NA	-15	N
DMPP + Ammonium Nitrate	NA	NA	NA	NA	NA	-20	N
DMPP + Liquid Manure	NA	NA	NA	NA	NA	-32	N
UAN + Nitrapyrin	West Lafayette, Indiana, USA	2 years	Continuous Corn	NA	Sub surface band application	-29	M
Urea + 2-amino-4-chloro-6-methyl pyrimidine (AM)	NA	NA	NA	NA	NA	-23	N
Urea + N-(n-butyl) thiophosphoric triamide	NA	NA	NA	NA	NA	20	N
Urea + hydroquinone	NA	NA	NA	NA	NA	-5	N
Controlled Release						-32	
Stabilized Fertilizer						-39	
Slow Release						-41	

A ... Halvorson et al. (2010a); B ... Halvorson et al. (2010b); C ... Halvorson et al. (2011); D ... Halvorson and Del Grosso (2012); E ... Halvorson and Del Grosso (2013); F ... Halvorson (unpublished); G ... Delgado and Mosier (1996); H ... Bremner and Blackmer (1978); I ... Bronson et al. (1992); J ... Skiba et al. (1993); K ... Sistani et al. (2011); L ... Shoji et al. (2001); M ... Burzaco et al. (2013); N ... Akiyama et al. (2010)

Enhanced efficiency fertilizers are object of interest of agronomic research in public institutions as well as in industry. The individual studies presented in Table 3 may provide an overview but should not be mistaken as complete. As mentioned above, results are compared on the basis of N_2O emissions, which are clearly reduced in most cases, and not in terms of efficiency improvements.

In addition to the studies in Table 3, it is important to also refer to a recent review by Snyder et al. (2014). These authors confirm the consistent emission reductions observed, while their review also includes studies beyond those quoted here. Differences, however, are evident between different regions and between studies. Nevertheless, the average factors listed in Table 3 are fully in line with especially the meta-studies cited that involve a large number of individual trials. Also most recent literature (Lam et al., 2015; Pfab et al., 2012) confirm this magnitude, and Akiyama et al. (2010) specifically mention an average reduction of 38% for nitrification inhibitors. As also the largest base of evidence presented in Table 3 is available for stabilized fertilizers (i.e. fertilizers combined with inhibitors) at nearly the same result, it is reasonable to adopt the quoted 38% of emission reductions in GAINS.

While tests on emission reductions most frequently do not directly regard mitigation costs, in the case of enhanced efficiency fertilizers, which are available on the market, cost data indeed is available, even if not for all components, but rather not in peer reviewed publications but in leaflets provided by farming extension service or other farmer-related information. Table 4 compiles relevant cost information.

Table 4: Costs of enhanced efficiency fertilizers

(calculated as costs in addition to those of regular fertilizer, in US$ per ton of fertilizer N applied)

Type	*Price (US $ per ton N)*	*Source*
Controlled Release		
Polymer Coated Urea*	348	Ransom (2013)
Controlled Release	917	Carson and Ozores-Hampton(2014)
Slow Release		
Slow Release	1569	Carson and Ozores-Hampton (2014)
Stabilized		
NBPT	151	Laboski (2006)
Super U*	372	Ransom (2013)
NI & UI**	105	Carson and Ozores-Hampton (2014)
Agrotain Plus	151	Laboski (2006)
Nitrapyrin	102	Laboski (2006)
N-Serve	150	Iowa Soybean (2012)

*Prices calculated with reference to a Urea price of $545/ton

**Prices available for inhibitors without fertilizer

This cost table shows, first of all, that two out of the three methods to reduce emissions have considerably higher costs, at least to-date. As “stabilized fertilizer” provides impressive emission reductions in a large number of studies at clearly lowest cost, inhibitors represent the primary recommendation of an enhanced efficiency fertilizer. In assessing the costs, we deliberately address the low end of the range, at 102 and 105 US $ per ton N, respectively. This is commercially available substrate today, and we find it reasonable not to assume significant price increases (or decreases) by 2030. Using an exchange rate of $1.2/€ this results in € 86 per ton N, which is just slightly lower than the € 100 per ton N of nitrification inhibitor used previously in GAINS (Winiwarter, 2005). The cost range is also consistent with information obtained from the fertilizer industry, indicating inhibitors to be available at costs marginally different to those of fertilizers (in the range of 5-10%).

While specific costs are not available, in agreement with the literature (Lam et al., 2015) we assume that application of inhibitors can also target manure to the same extent. We conclude that it is possible to reduce N_2O emissions by means of nitrification inhibitors (to be understood to represent chemical inhibitors in general) by 38% at costs of 86 € per ton N applied. This figure does not consider savings in fertilizer applied, which is referred to consistently in the scientific literature, but it is not clear how that can be translated into practice as quantitative data is lacking. The experiments refer to emission reductions at constant fertilizer application rates, so also in modelling we assume only the emission factor to be affected, not the fertilizer consumption. Inhibitors provide reductions of ammonia emissions and nitrate leaching, too. The extent of such reductions (urease inhibitors will diminish the release of ammonia from urea and manure, while nitrification inhibitors will decelerate nitrate formation that could be leached) was not studied here, but cannot be ignored. For simplicity and as the estimate remains conservative for not addressing fertilizer savings, we refrain from distinguishing direct and indirect soil emissions, and apply reductions to all emissions related to soil nitrogen input.

This extended dataset estimates measured N_2O emission reductions for a given amount of fertilizer applied. This is a significant advancement compared to the previous approach, where we allowed for reduced fertilizer application (and proportional emission reductions). Measurements overwhelmingly demonstrate that reductions of emissions exceed what was thought possible previously. Still we think this estimate is conservative, as inhibitors that keep nitrogen available for the plant and avoid losses might also allow for reduced fertilization rates. Such additional improvement potential is not considered. The cost efficiency of this option improved compared to the previous implementation (less costs per ton avoided) basically due to the higher emission reductions that now are believed to be possible.

3. Further mitigation options studied

In the scientific literature, material is available on even more options to reduce soil emissions of N_2O. For instance certain management operations on agricultural soil will inevitably influence soil conditions and thus may also result in altered N_2O emissions. Specifically, this refers to soil tillage – studies typically differentiate intensive, conventional, conservation tillage and no till operations. While the “no tillage” option is often seen as a possibility to increase soil carbon content and thus contribute to CO_2 sequestration (e.g., Pellerin et al., 2013) it tends to be associated with increased N_2O emissions: some authors, e.g. Smith and Conen (2004) even claim any carbon sequestration can be negated by N_2O emitted. Variation between individual studies is high, however, and no definite conclusion can be drawn on the impact on N_2O emissions.

The same is also true for crop rotation: depending on the assumptions taken and the crops used, results are not conclusive on the impact on soil condition and subsequent N_2O emissions. Crop rotations that include legumes as part of their rotation (or as intermediate cover crop) may provide additional Nr to soil that can be deducted from other fertilizer needs, and thus result in lower N_2O emissions as long as associated with reduced fertilizer application. Individual studies do suggest that certain crops (e.g. clover) can enhance nitrogen efficiency (O'Brien et al, 2014, p 112).

Relationships between changed management (tillage and crop rotation) and N_2O emissions seem to exist and it will be advisable to further monitor progress in the field, as there may be a potential for relatively simple abatement options that should not be ignored once the relationships become more transparent.

As the emissions of N_2O necessarily rely on nitrogen, the mode and the chemical form of fertilizer application (in addition to the amount, which is covered in the IPCC methodology) is closely associated with the actual release process. Different types of nitrogen fertilizers are available on the market, and the individual choice may be guided by agronomic reasons. The chemical form may also influence N_2O emissions. A body of scientific literature exists that tries to look into the impact on N_2O emissions due to change in fertilizer applied (Venterea et al, 2015, Venterea et al, 2010, Sistani et al, 2011, Plester et al, 2010, Maggiotto et al., 2002, Snyder et al., 2009, Bouwman et.al., 2001) But the results of our extensive literature study is not conclusive. For the time being changing fertilizer type is not considered an option in GAINS. More evidence needs to be collected, also regarding limited applicability under certain conditions (e.g., regarding specific crops) before selection of a specific fertilizer can be included as a GAINS emission abatement option.

4. Discussion and uncertainties

The GAINS model approaches emission reductions by evaluating explicitly defined measures, thus in the previous chapters scientific literature on such specific measures was taken advantage of. It is also of interest, however, to note which levels of abatement have been discussed elsewhere, when not specifically referring to the pathway of achieving these results. An overall estimate of possible N_2O emission reductions has been provided by Oenema et al. (2013), by way of improving the nitrogen use efficiency and by manure management. These authors assume an overall reduction of emissions of 41% globally by 2050 due to efficiency improvements, and even 60% when non-technical measures such as reducing food losses and diet changes are implemented. For comparison, Davidson (2012) estimates a potential of up to 50% emission reductions, while the differences in emission scenarios reported by Bouwman et al. (2001) range in the order of 35%. The specific reductions proposed for GAINS in the current paper of up to 40%, which have been taken from studies on specific measures, thus seem to be of a reasonable order of magnitude. Differences in emission reduction estimates remain, which is not surprising considering the limits in scientific understanding of the variability of soil microbial processes, the immediate cause of N_2O formation.

In the current paper, we attempt to select measures cautiously, only if very good reasons exist that they can be applied successfully, and to an extent that can be well justified. For these reasons we were, at this stage, not able to quantify potentially interesting technical options like giving preference to specific fertilizer types or tilling strategies, where available information showed a mixed response. Neglecting such potentially cheap management options to reduce emissions may increase overall costs of measures, as emission reductions now will be captured in the cost curve only by the more expensive abatement technologies. Moreover, no account was made of economic gains due to fertilizer savings (or yield increases) nor technical progress over time. Also, we limit emission reductions implemented in GAINS to the direct experimental results – decrease of fertilizer consumption for most options, and decrease of emission factors for inhibitors while maintaining the level of fertilizing – even if there are good reasons (and some indications) why emissions may decrease even more strongly. Finally, no agronomical improvements have been considered from the current state (e.g., by combining the promising options described here, VRT and inhibitors), except for the improvements implicitly accounted for in the business-as-usual; fertilizer and animal projections imported from CAPRI.

For the above reasons, it seems useful to reflect the uncertainties associated with the assumptions also in the cost curve, instead of assigning just one fixed average reduction/abatement cost to each measure, irrespective of the specific conditions that cannot be covered individually. Capturing the respective uncertainties by way of a full uncertainty analysis also extends beyond the scope of this study. Instead, uncertainty here is represented by dividing each of the promising new options into a “low-cost”, “mean” and “high-cost” option, and apply these uniformly over all countries to create a cost range (see below).

5. Summary of GAINS updated cost curve

Using the information gathered on the individual measures of emission reductions (section 2), a cost curve was established guided by the following principles: (i) measures cannot be applied simultaneously, i.e. only one measure is in place at one time; (ii) the cost curve starts with the cheapest option (in €/ton N_2O abated); (iii) marginal costs are calculated assuming a more stringent measure replaces the previous measure, i.e. based on differential costs by differential emissions reduced. No differentiation is made by country.

This approach basically has been used already in the previous implementation of GAINS (Winiwarter, 2005; Höglund-Isaksson et al., 2013), distinguishing “fertilizer reduction”, FERT_RED (mechanical adjustments allowing to reduce wastage in the application process) “fertilizer timing”, FERTTIME (directing fertilizer temporal availability to the needs of plants), “nitrification inhibitors”, NITR_INH (agrochemistry), and “precision farming”, PRECFARM (high-tech abatement options). In the proposed extended GAINS version, the individual options have been altered.

In comparison to the 2013 implementation in GAINS, one new abatement technology was added, “VRT” for variable rate technology. Parameters were changed also for inhibitors as discussed in detail in section 2 above – now referred to as “INHIB” (fertilizers stabilized with inhibitors). In line with arguments provided in section 4, these two elements have been split each in three parts in the cost curve assuming (1) equal share of emission reduction for each of the three respective sub-elements and (2) 30% decrease/increase of marginal costs of the “high” and the “low” vs. the “medium” cost variant (identified by “H”, “L” and “M” added to their names).

As described earlier, we understand that efficiency improvements of 6% accounted for in the 2013 implementation in GAINS, referred to as the measure FERT_RED, representing the easiest and cheapest “mechanical” options to reduce N_2O, is already assumed to be covered by efficiency improvements in the CAPRI model for the reference projections (Capros et al., 2013). This requires an adjustment of scales, as experimental data of emission reductions have been derived comparing to a current level of efficiency, and any mitigation potential by 2030 needs to take into account these efficiency improvement in the reference projections. As a consequence, emission reductions compared to 2030 reference projections, as reported in Table 5 are consistently smaller than those derived from the experiments in section 2. The remaining emission level now needs to be scaled against the reference emission projections, which reflect the 6% improvement of efficiency. Remaining emission reduction for VRT it is 19% (from originally 24%)[1], for inhibitors 34% (from originally 38%)[2] and for full-scale precision farming 36% (instead of 40%)[3]. These reductions apply to the reference emission projections of N_2O due to nitrogen input to soils, which is the major part of N_2O emissions (see section 1), exactly that part to which the measures discussed in this report apply.

The new sort order of technologies, the total emission reductions and the marginal costs are consequences of the changes introduced (Table 5). In addition to the scale adjustment, which leaves FERT_RED at 0% emission reduction, the principle (i) outlined above would not allow two options to be applied at the same time. Instead, the cheaper option in terms of marginal costs is selected, at least to the extent of its reduction potential. As VRT is both cheaper and has a higher reduction potential than FERTTIME, the latter measure finds no application in the new cost curve.

Due to the considerable reduction potential at moderate costs, VRT represents the most cost-efficient technology at marginal costs around 20 €/ton CO_2-eq. VRT may be seen as a cost-efficient aspects of precision farming. Considering the significant technological progress renders this option quite realistic compared to information available previously. Also INHIB is available at lower costs than previously, near 40 €/ton CO_2-eq – in this case, this is due to enhanced emission reductions at the same cost level. The three levels available for both VRT and INHIB reflect the uncertainty inherent in an estimate of emission reductions and costs and allow for a smoother market introduction reflecting uncertainties to the extent currently possible. Finally, we assume further precision farming options are available – with the same costs (per ton of N applied) as previously (Höglund-Isaksson et al., 2013, p. 62), and with marginally increased emission reduction (36% compared to 34% of INHIB-H, marginal costs of 1070 €/t CO_2-eq are derived.

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[1] -19% = (1-0.24)/(1-0.06)-1

[2] -34% = (1-0.38)/(1-0.06)-1

[3] -36% = (1-0.40)/(1-0.06)-1

Table 5: Emission reductions and costs implemented in the updated GAINS model.

	emission reduction (different to projection)*	EF unabated [t N_2O/t N]	EF abated [t N_2O/t N]	costs [M€/t N]	emissions reduced by [t N_2O/t N]	marginal costs [€/t CO_2-eq]**
FERT_RED	0%	0.031	0.031	0	0	--
VRT_L	6%	0.031	0.029	0.000008	0.0020	12.8
VRT_M	13%	0.031	0.027	0.000019	0.0039	18.4
VRT_H	19%	0.031	0.025	0.000033	0.0059	23.8
INHIB_L	24%	0.031	0.023	0.000046	0.0074	26.1
INHIB_M	29%	0.031	0.022	0.000063	0.0089	37.3
INHIB_H	34%	0.031	0.020	0.000086	0.0104	48.3
PRECFARM	36%	0.031	0.020	0.000302	0.0111	1069.7

*) figures shown here consider improvements due to FERT_RED, thus are smaller than the reductions presented in section 2

**) marginal costs calculated based on a global warming potential of 310 for N_2O

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