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Green economy thinking and the control of nitrous oxide emissions ☆

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A B S T R A C T

As a potent greenhouse gas and contributor to stratospheric ozone depletion, nitrous oxide (N_2O) represents a global pollutant of growing concern. We use the N_2O example to consider the potential for Green Economy thinking to promote sustainability through emission reduction. A fundamental barrier to change arises from the distinction between 'Sector View' (green actions consistent with improved profit) and 'Societal View' (incorporating the value of all externalities). Bringing these views closer together requires a long-term perspective, while counting all co-benefits of taking action. N_2O control should be considered within the context of the wider nitrogen cycle, with an emphasis on improving full-chain nitrogen use efficiency (NUE_{fc}), exploiting a combination of technical measures in agriculture, industry, transport, waste water management and other combustion sources. Avoiding excessive meat and dairy consumption by citizens in developed countries can substantially

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reduce N_2O emissions. These measures offer many options for low-cost control of N_2O emissions, while reducing the health and ecosystem threats of other N pollution forms. In order to bring the 'nitrogen green economy' forward, a much stronger public profile is needed to motivate citizens' actions and to encourage investment in bringing new technologies to profitability. A recent estimate suggests that improving global NUE_{fc} by 20% would provide a N-saving worth ~23 billion USD to business, plus health and environmental benefits worth ~160 billion USD. The value of externalities highlights the green economy case for governments to develop a suite of instruments to go further in controlling N_2O emissions than the Sector View would typically allow.

1. Foundations of a developing nitrogen green economy

There are many definitions of the green economy. For some, the reference to 'green' implies a link to agriculture. For others the idea of the green economy encompasses all the economic opportunities arising from actions that promote sustainability, improving "human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP, 2010). The phrase 'green growth' is also frequently used, focusing on the contribution of environmental technologies to a growing economy (OECD, 2011), for example as measured by gross domestic product. Allen and Clouth (2012) provide a summary of recent perspectives and definitions in the Green Economy, also noting its central position as a theme of the Rio+20 declaration (UN, 2012).

Diverse points of view are also illustrated by the example of agriculture. In this case, while some have emphasized the benefits of 'sustainable intensification' as a means to reduce environmental degradation, others have pointed to a rather different vision that seeks to avoid intensification (see discussion by Garnett and Godfrey (2012)). The latter group would instead encourage a move away from dependence on external fertilizer inputs in conventional farming practices (Kotschi, 2013), focusing on the role of "organic resource inputs and natural biological processes to restore and improve soil fertility" (Herren et al., p. 68 in UNEP, 2011).

Whatever the outcome of this hot debate, there are strong shared challenges, with many available actions to reduce nitrous oxide (N_2O) emissions while contributing to improved economic performance. This applies whether the focus is on industrial or agricultural emissions of N_2O, whether the local paradigm is one of intensive or extensive management, and whether the focus is on utilizing or avoiding external inputs. In all cases, there is a need to develop consensus around the common opportunity for improving production efficiency, business profits and citizens' welfare through environmentally targeted measures.

It is essential to recognize the link to the wider nitrogen cycle. This means that strategies to reduce N_2O emissions from a climate perspective can be developed that simultaneously lead to overall reductions in nitrogen losses (Oenema et al., 2011; Sutton et al., 2013a). The nitrogen saved contributes to improving food production, while reducing its contribution to air, land and water pollution. Such co-benefits can be critical in developing the 'green economy case' to motivate the changes needed.

2. Contrasting green economy perspectives

The green economy includes issues related to profitability of production sectors and related to societal welfare. This leads to two distinct perspectives regarding N_2O control, especially as this relates to the effect of greening on product prices and the decisions of producers and consumers.

Sector View: according to this view, it needs to be shown that actions taken to reduce N_2O and other N emissions are of net financial benefit to the business sectors responsible for those emissions. This can be illustrated for agriculture, where the financial value of fertilizer savings associated with improved N management may be combined with other market advantages, with the aim that overall economic benefit exceeds the cost of low emission practices. In short, the green economy should improve profits.

Societal View: according to this view, all the costs and benefits of N_2O-related management options should be considered. This approach accounts for both the direct and indirect costs and benefits, and seeks to internalize issues related to societal wellbeing. In addition to business profitability, the benefits of improved N management and reduced N_2O emissions on climate, human health and biodiversity need to be quantified in order to evaluate the net societal benefit. This approach integrates the implications for natural capital and all ecosystem services.

Recent analyses (Brink et al., 2011; Birch et al., 2011; van Grinsven et al., 2013) suggest that the economic benefit of reducing environmental externalities can be several times the direct sector benefits of taking action to reduce N emissions. However, such estimates are often considered only as a notional 'willingness to pay' rather than an actual cost paid by society. Because of this, and given the voice of different economic sectors, the Sector View often dominates a green economic perspective in practice. In essence, there may be an economic case for society as a whole to take certain actions to reduce emissions. However, to motivate change, it will often need to be shown that the approach can also increase sector profits.

In principle, the Sector View should naturally also integrate the climate, environmental quality and health benefits of mitigation action. The limitation here is that, while the direct business costs and benefits accrue to the sector, the sector only shares a small fraction of these wider societal benefits. This represents the well-known paradigm of the 'Tragedy of the Commons' (Hardin, 1968), where it is typically in the economic interest of an individual or company to exploit a reserve, since they are only exposed to a small share of the associated environmental costs. It therefore becomes the task of society (governments, other business groups, civil society) to encourage the changes needed to maximize net societal benefit.

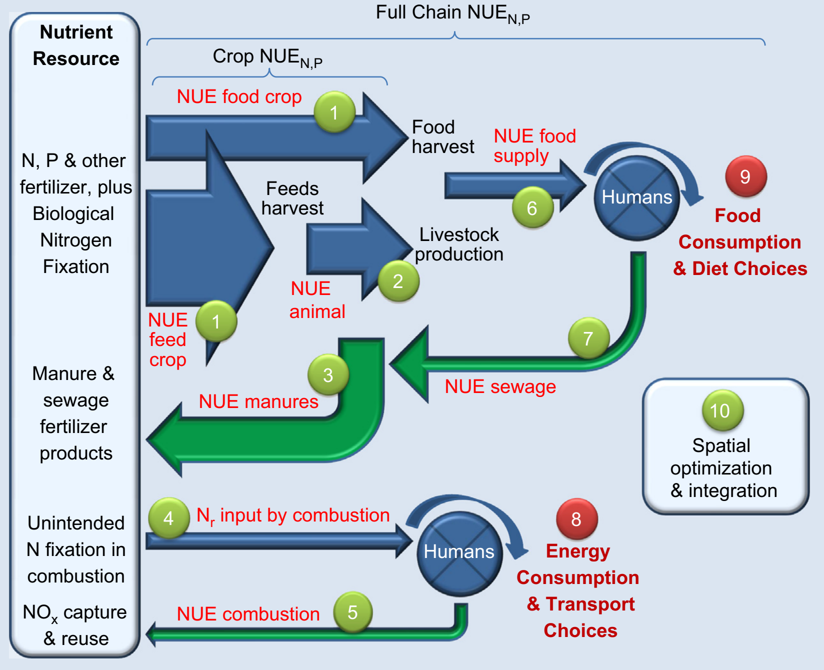
The net societal benefits of N_2O control and improved N management point strongly to the need to further develop financial frameworks to foster increased adoption of N_2O controls. The inclusion of N_2O in existing greenhouse gas emission trading schemes still requires further development (Davidson, 2012; DECC, 2011). However, by only considering climate protection, this substantially underestimates the full value of N_2O mitigation as part of a wider package of improved nitrogen management. The extent of these added benefits highlights the potential to support N_2O emission reduction, drawing on suitable packages of incentives, levies, regulation or voluntary approaches according to regional context.

3. Performance indicators for N_2O in the green economy

While total N_2O emissions estimates are naturally the most basic performance indicator, other indicators should be considered, such as global atmospheric N_2O concentrations. It is also important to consider indicators that allow regional differentiation and evaluation in relation to the green economy. Among these, Nitrogen Use Efficiency (NUE) is a key indicator, which may be expressed on several different scales (Box 1).

At its simplest, NUE is the ratio of nitrogen in an intended product divided by the amount of nitrogen used to make that product. NUE can be calculated from the field and farm scales to national and global scales. *Our Nutrient World* proposed a focus on full-chain nitrogen use efficiency (NUE_{fc}), considering all sources of input nitrogen, in relation to products consumed by humans. In this way, component terms, such as NUE for crop and livestock agriculture, for aquaculture and for food processing are incorporated, as well as the efficiency in which industrially produced N is used. The full-chain NUE indicator offers substantial flexibility to countries and sectors on their choice of the most effective control strategies (Box 1).

Box 1–Minimizing N_2O emissions in the context of improving full-chain nitrogen use efficiency.



Reactive nitrogen flow can be seen as a cycle from resource through use (blue arrows), with recycling (green arrows). The system is driven by the 'motors' of human consumption. Circles highlight ten key actions to increase Full-chain Nitrogen Use Efficiency (NUE), contributing through improved technical efficiency (green circles) or altered consumption patterns (red circles):

Agriculture
1. Improving nutrient use efficiency in crop production,
2. Improving nutrient use efficiency in animal production,
3. Increasing the fertilizer equivalence value of animal manure,

Transport and Industry
4. Low-emission combustion and energy-efficient systems, including renewable sources,
5. Development of NO_x capture and utilization technology,

Waste and Recycling
6. Improving nutrient efficiency in fertilizer and food supply and reducing food waste,
7. Recycling nitrogen and phosphorus from waste water systems, in cities, agriculture and industry,

Societal consumption patterns
8. Energy and transport saving,
9. Lowering personal consumption of animal protein among populations consuming high rates,

Integration and optimization
10. Spatial and temporal optimization of nutrient flows.

(Source: Sutton et al., 2013a,b).

Other useful indicators include regional nitrogen balances (surpluses and deficits), with the aim to use all available N resources. It should also be noted that the use of nitrogen balances complements NUE, giving a more complete picture. The contrasting case of intensively reared pig meat and extensively reared beef can serve to illustrate the difference. A large intensive pig farm will typically be operated with much higher livestock NUE (ratio of N in product to N in feed) than for extensive beef production, but because of high stocking rates it will be associated with locally high a larger local surplus of N (expressed on a local area basis), associated with locally high pollution losses. Consideration of both indicators therefore has the advantage of fostering both improved NUE and reduced local surpluses according to the potential for each system.

The consideration of NUE and N balances links control of N_2O emissions with other N losses to the environment in the form of nitrogen oxides (NO_x), ammonia (NH_3), nitrates (NO_3) (Skiba et al., 2012). Better full-chain NUE therefore contributes to simultaneous mitigation of N_2O and other N pollution (Reay et al., 2012; Sutton et al., 2013a).

It is relevant to compare strategies for specific N_2O control and for overall NUE improvement. In the case of specific N_2O control, the co-benefits depend on other synergies. For example, better fuel combustion in vehicles can reduce N_2O emissions, associating reduced emissions with improved process efficiency.

The use of enzyme inhibitors in agriculture offers another example of green economy opportunities. In this case, a compound delays microbial conversion between nitrogen forms in the soil. Where the only effect is to reduce N_2O emissions, there will be few co-benefits, as the N fraction

Box 2–Green economy perspective on N_2O mitigation through improved fertilizer techniques. (Akiyama et al., 2010; Chambers and Dampney, 2009; Hyatt et al., 2010; IFDC, 2012; Liu et al., 2013; Motavalli et al., 2008; Sanz-Cobena et al., 2012; Savant and Stangel, 1990; Smith et al., 2012; Upadhyay et al., 2011; Zaman and Blennerhassett, 2010; Zaman et al., 2013)

Example technique	Effects	Costs and other information	Green Economy Outlook
Nitrification inhibitors (NI) (e.g., nitrapyrin, DCD, DMPP).	Slows the conversion of NH_4 to NO_3, reducing the potential for N_2O and N_2 losses and NO_3 leaching [1]	Often applied separately from fertilizer, increasing labour and fuels costs.[2] Agronomic benefit can be small.[3] Used to provide management flexibility.	Potential for cost saving by new products and testing effects on NUE and yield. Upscaling though legislation would be expected to reduce costs and increase agronomic benefit.
Urease inhibitors (UI) (e.g. NBPT)	Slows conversion of urea to NH_4, allowing improved NUE by reduced NH_3 losses[4,10] and delayed N supply.	Additional cost of amending urea is currently US$50 per t. Depending on context, can contribute significantly to N_2O emission reduction, but not in all situations[1,4,9]. Also reduces indirect N_2O emissions resulting from NH_3.	Combination of UI and NI effectively mitigate NH_3 and N_2O. Potential for substantial cost saving by inclusion into urea at source and by legislation.
Slow and controlled release fertilizers (SRFs & CRFs) (mainly urea based)	Slows nutrient release, leading to reduced NH_3 and N_2O emissions and to less NO_3 leaching.	High cost per unit of N compared to conventional fertilizers. Use currently limited to niche non-agricultural markets. Although not always effective[1], can reduce N_2O emissions by 35%, more effective on grasslands.[7] Reduces need for split fertilizer applications, so may be cost neutral.	Clear guidelines on environmental and management criteria must be developed to use SRFs and CRFs as effective N_2O inhibitors
Urea Deep Placement	Placing 'urea super-granules' into the soil, improves NUE by reducing NH_3 losses and by targeting roots.	Reduced N losses and improved NUE (with 15-20% increase in incremental yield [8]) point to expected reduction in N_2O losses.	Adopted on a wide scale in Bangladesh since 2008, motivated by government need to reduce national subsidies following increases in world fertilizer price.

[1]Akiyama et al. (2010); Zaman et al. (2013). [2]N_2O reduced by 38% [1], but costs can be 10% higher than N fertilizer alone.
[3]Lui et al. (2013), Upadhyay et al. (2011). [4]Zaman et al. (2009); Sanz-Cobena et al. (2012). [5] Zaman and Blennerhassett (2010)
[6]Hyattet al. (2010). [7]Motavaliet al. (2008). [8]Savant and Stangel (1990); IFDC (2012).
[9]Smith et al. (2012). [10]Chambers and Dampney (2009).
Note: DCD is dicyandiamide; DMPP is 3,4-dimethylpyrazole phosphate; NBPT is N-(n-butyl) thiophosphoric triamide

lost as N_2O is typically $<10\%$. However, where the inhibitor simultaneously reduces other major N losses (i.e., denitrification, NO_3 leaching, NH_3 emissions), this can improve NUE (Box 2).

The outcome is that measures specifically targeted at N_2O mitigation do not necessarily also lead to an improvement in NUE_{fc}. By contrast, measures primarily focused on improving NUE contribute to a reduction in N_2O and other N emissions per unit of product produced. This way of thinking is much more constructive than an earlier scientific focus on 'pollution swapping'. While there are both trade-offs and synergies involved in managing the N cycle, an emphasis on improving full-chain efficiency provides the key to maximizing the co-benefits.

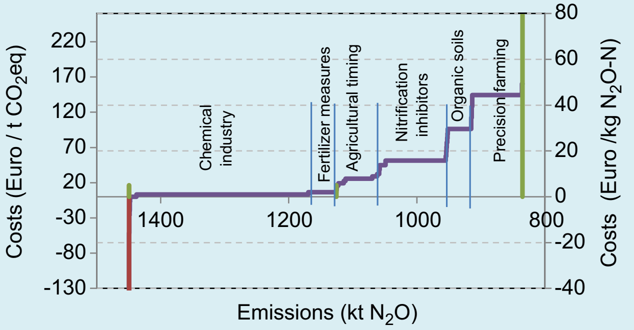
4. Costs and benefits of N_2O mitigation in the context of the N-cycle

The potential of improving NUE to the green economy can be illustrated by approximate calculations based on the *European Nitrogen Assessment* (Brink et al., 2011; van Grinsven et al., 2013) and *Our Nutrient World* (Sutton et al., 2013a). These provide a starting point for discussion, while encouraging improvement in cost-effectiveness of the different options.

A framework for the discussion has been provided by the proposal for an aspirational target to improve nitrogen use efficiency by 20% by the year 2020 (Sutton et al., 2013a). Applying this as a relative improvement from 2008 at national-level led to a global saving of 23 million tonnes of nitrogen, worth an estimated 23(18–28) billion US dollars. The value of annual benefits to the environment, climate and human health was much larger, estimated at 160(40–400) billion US dollars. An indicative mitigation cost was estimated at 12(5–35) billion US dollars (compare Box 3). These values provide a basis to discuss the essential propositions of the Nitrogen Green Economy.

Firstly, it is estimated that there are many options for businesses emitting N_2O where the value of the N saved through improved NUE is larger than the cost of taking action. The ongoing challenge is to further up-scale such methods to bring down costs, and thereby strengthen the economic case for

Box 3–Estimated costs of Europe-wide N_2O mitigation based on 2020 (Drawing on Winiwarter et al., 2010).



The cost increments are shown for reducing N_2O emissions in Europe from a base-line projection for 2020 of 1440 kt (red bar) down to 835 kt (maximum technical feasible reduction, green bar) based on measures in the GAINS model (Winiwarter et al., 2010). Half of the mitigation is very low cost (<5 €/ton CO_2-eq), especially from improving fertilizer efficiency in agriculture. All industrial mitigation options are used (flue gas treatment in nitric and adipic acid plants, and fluidized bed combustion). It is assumed that the EU emission trading system (ETS) provides sufficient incentive for companies to take advantage of abatement, so low-cost measures are included in the baseline. Further reductions possible through reduced meat and dairy consumption are not included.

action. Incentives may be needed to bring initially uneconomic techniques into profitability, as a catalyst for stimulating green development.

Secondly, the estimates show that the benefits of improving NUE for the environment, climate and human health are much larger than the direct costs and benefits to business. This means that there is a very strong economic case for society to develop actions that stimulate improved NUE with reduced N_2O emissions.

5. Integrating N_2O into aspirations for green production and consumption

There is still a long way to go in mainstreaming N_2O mitigation into the Green Economy. Until recently, N_2O mitigation has often taken a back seat, compared with efforts to reduce CO_2 and CH_4. There is the opportunity for this to change dramatically as N_2O offers many low hanging fruit, with many measures in agriculture available at less than 5 €/ton CO_2-eq abated (see Box 3). A comparative assessment by Winiwarter et al. (2010) clearly shows that in this cost range CO_2 mitigation measures are under-represented, as N_2O mitigation is more cost effective. Mitigation of N_2O should also be seen in the context of mitigating the wider impacts of nitrogen pollution. This includes reducing adverse effects on air pollution (such as particulate matter and tropospheric ozone formation), water pollution (including effects on drinking water quality, groundwater reserves and eutrophication of rivers, lakes and seas) and threats to ecosystems and biodiversity, such as through eutrophication from atmospheric nitrogen deposition.

Whether nitrogen is in excess, as in many developed countries, or in shortage – posing a risk for soil degradation and land-use change in developing countries – improving NUE_{fc} offers simultaneous benefits for the global green economy. It improves the prospects for human food production, while simultaneously reducing multiple environmental threats.

It is vital to consider N_2O control within the context of future societal aspirations for sustainable production and consumption. Central here is the dominating influence of livestock farming on the global agricultural system, where an estimated 82% of nitrogen in harvests (including forage) goes to feed livestock: less than 20% of nitrogen in harvests feeds humans directly (Sutton et al., 2013a). At the same time, citizens in many countries are consuming more protein than needed. For example, in Europe the average citizen consumes 70% more protein than is necessary for a healthy diet, based on dietary guidelines (Reay et al., 2011).

There are several consequences of these observations. Firstly, citizens in the developed world are setting a standard for food consumption patterns that is far from sustainable, while at the same time leading to significant additional health risks through over consumption. Secondly, many citizens in the developing world are aspiring to western food consumption patterns. While there is a critical need for improved diets among the world's poorest, there is a matching challenge in the developing world economy where increasing personal consumption of animal products, combined with increasing world population, is setting the stage for a substantial worsening of N_2O and N pollution. Based on current FAO and pollution scenarios, fertilizer usage and N pollution levels may increase globally by 70% by the year 2050, unless action is taken (Sutton and Bleeker, 2013).

Strategies to control N_2O emission therefore need to incorporate several approaches. As the first step, measures that improve NUE combined with targeted N_2O reduction are an obvious priority. This will need to be combined with strategies that foster behavioral change to avoid excessive consumption of animal products (Reay et al., 2011; Davidson, 2012; Sutton et al., 2013a).

Reducing excess animal consumption in the developed world is expected to have several consequences: (a) N_2O and other N emissions would substantially reduce, (b) full-chain NUE would increase (Box 1), (c) the fraction of income spent on food would tend to decrease, (d) the incidence of obesity- and cardiovascular-related illness may be expected to decrease, (e) new societal aspirations may emerge in developing countries, where those with rapidly increasing income seek more optimal dietary consumption patterns, reducing global health risks associated with over consumption and (f) increased agricultural land would become available to support food security goals among the world's most vulnerable populations.

These interactions raise a whole host of questions, associated with improving quality of life and developing competitive advantages. However, they must become central to the developing debate on N_2O, nitrogen and the green economy.

6. Options to foster change

There are a wide range of options for global society to develop the technical and behavioral change approaches outlined here. These include the fostering of innovative improved NUE techniques in agriculture, aquaculture and waste management. In the industrial sector, there are opportunities for combustion-source oxidized nitrogen recovery, with potential co-benefits for N_2O mitigation (Action 5, Box 1).

Capacity building efforts are also needed to diffuse existing technologies and train in low N_2O emission approaches. Better N use may be encouraged by the avoidance of subsidies that encourage overuse of nitrogen. At the same time, the case of Bangladesh (Box 2: urea deep-placement, UDP) shows how an existing nitrogen subsidy motivated government action to improve NUE. Although the UDP technology for lowland rice has been known for many years (e.g. Savant and Stangel, 1990), its upscaling was initially limited by the supply of urea-supergranules (USG) suitable for deep-placement in the soil. In 1996, this obstacle was addressed with the distribution of village level urea compactors capable of converting fine urea prills (~3 mm diameter) into the 'USG' (~15 mm length). With increased farmers' access to USG, adoption of the UDP technology escalated significantly. This fertilizer application technology resulted in an average saving of urea fertilizer of 33% compared with the farmers' normal practice of broadcast application of urea (Roy and Hammond, 2004). However, with the increased price of fertilizers (including urea) associated with the energy crisis of 2007, the Bangladesh government became exposed to larger fertilizer subsidy costs. This economic constraint therefore motivated the government to encourage wider adoption of the UDP technique substantially across Bangladesh (IFDC, 2012).

Other options include the pricing of N pollution through appropriate levies, subsidies or tradable permits, which catalyze new markets in improved NUE until they can become self-sustaining. Here one can expect an ongoing debate on the relative merit of regulatory, economic and voluntary approaches (Sutton et al., 2007). Where voluntary approaches are favoured, the key is to quantify the improvements made, and clearly set the ambition level anticipated by society. Interventions should especially consider how to allow the costs of taking action by emission sectors to be transferred to consumers. The proposal to refine national, regional and local NUE and N-balance indicators holds the prospect both for improved benchmarking and target setting.

Finally, communication strategies for N_2O and wider N management need substantial further development. Promoting the market benefits of Clean-N technologies will encourage environmental competition between businesses. At the same time, better public communication is needed to explain the health, environmental and price benefits of optimizing consumption rates of meat and dairy products (Sutton et al., 2013b).

7. Conclusions

- There are many options available to control N_2O emissions that are cost-effective compared with other greenhouse gases.
- A fundamental barrier to change is the need to recognize the distinction between the 'Sector View' (green actions consistent with improved profit) and the 'Societal View' (incorporating the value of all externalities). Bringing these views closer together implies the need for a long-term perspective within the context of the wider nitrogen cycle, while counting all the co-benefits of taking action.
- In arable and livestock agriculture, aquaculture and waste management, N_2O measures that are focused on improving nitrogen use efficiency (NUE) benefit the Green Economy by saving nitrogen fertilizer as a valuable resource.
- For industry and combustion sources, economic advantages may be found in reducing N_2O losses, through improving process efficiency, while developing market share through green reputation.
- Reducing excess animal consumption in the developed world would improve full chain NUE, reducing N_2O and other N emissions, while fostering societal aspirations across the world to avoid excess livestock consumption. While this would require a scale of change that is counter to current trends, it would simultaneously offer opportunities to reduce the fraction of income spent on food, the incidence of obesity- and cardiovascular-related illness and the amount of land needed to support food security goals.

- It is essential to investigate optimal consumption patterns alongside efficiency improvements, especially where the latter result in price reductions which lead to more rapid rates of consumption increase. Such increases in consumption can otherwise offset the gains in reducing N_2O emissions derived from improving efficiency.
- Recent valuations show that the total economic benefits of reduced nitrogen losses substantially exceed the benefits of these actions to the emitting sectors. The additional benefits include reduced threats to human health and ecosystems through improved air, soil and water quality.
- The linking of efficiency savings for business with the internalization of environmental benefits provides a strong case for simultaneously reducing N_2O and other N emissions. Incentives are needed to encourage new developments in the Nitrogen Economy and to act as catalysts to overcome the barriers to change.
- Options include fostering innovative high-NUE techniques, capacity building and training in low N_2O emission approaches, avoidance of environmentally damaging N subsidies, internalizing the price of N pollution through appropriate levies, subsidies or tradable permits, and improving communication to promote the market benefits of Clean-N technologies.

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References

Akiyama, H., Yan, X., Yagi, K., 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. Global Change Biol. 16, 1837–1846.

Allen, C., Clouth, S., 2012. A guidebook to the Green Economy. Issue 1: Green Economy, Green Growth, and Low-Carbon Development – history, definitions and a guide to recent publications, UN Division for Sustainable Development.

Birch, M.B.L., Gramig, B.M., Moomaw, W.R., Doering III, O.C., Reeling, C.J., 2011. Why metrics matter: evaluating policy choices for reactive nitrogen in the Chesapeake Bay water-shed. Environ. Sci. Technol. 45, 168–174.

Brink, C., van Grinsven, H., Jacobsen, B.H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., van Oorschot, M., Webb, J., 2011. Costs and benefits of nitrogen in the environment. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, pp. 513–540. (Chapter 22).

Chambers, B.J., Dampney, P.M.R., 2009. Nitrogen efficiency and ammonia emissions from urea based and ammonium nitrate fertilisers. International Fertiliser Society, York, UK., pp. 61–20. (Conference Proceedings).

Davidson, E.A., 2012. Representative concentration pathways and mitigation scenarios for nitrous oxide. Environ. Res. Lett. 7, 024005, http://dx.doi.org/10.1088/1748-9326/7/2/024005. (7 pp).

DECC, 2011. Government Response to the Consultation on the UK Unilateral Opt-in of Nitrous Oxide Emissions From Nitric Acid Production Into Phase II of the EU Emissions Trading System. UK Department of Energy and Climate Change, London 〈www.gov.uk/government/uploads/system/uploads/attachment_data/file/43239/1668-govt-resp-cons-n20-optin.pdf〉.

Garnett, T., Godfrey, C.J., 2012. Sustainable Intensification in Agriculture. Navigating a Course Through Competing Food System Priorities. Food Climate Research Network and the Oxford Martin Programme on the Future of Food. University of Oxford, UK.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.

Hyatt, C.R., Venterea, R.T., Rosen, C.J., McNearney, M., Wilson, M, Dolan, M.S., 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J 74, 419–428.

IFDC, 2012. Fertilizer Deep Placement (FDP). International Fertilizer Development Center. 〈http://www.ifdc.org/Technologies/Fertilizer/ Fertilizer_Deep_Placement_(UDP)〉.

Kotschi, J., 2013. A Soiled Reputation: Adverse Impacts of Mineral Fertilizers in Tropical Agriculture. Heinrich Böll Stiftung (Heinrich Böll Foundation). WWF Germany.

Liu, C., Wang, K., Zheng, X., 2013. Effects of nitrification inhibitors (DCD and DMPP) on nitrous oxide emission, crop yield and nitrogen uptake in a wheat–maize cropping system. Biogeosciences Discuss. 10, 711–737.

Motavalli, P.P., Goyne, K.W., Udawatta, R.P., 2008. Environmental impacts of enhanced-efficiency nitrogen fertilizers. Crop Manage. 〈http://www.plantmanagementnetwork.org/pub/cm/symposium/enhanced/impacts〉.

OECD, 2011. Towards Green Growth. Organization for Economic Cooperation and Development, Paris.

Oenema, O., Salomez, J., Branquinho, C., Budňáková, Černák, P., Geupel, M., Johnse, P., Tompkins, C., Spranger, T., Erisman, J.W., Pallière, C., Maene, L., Alonso, R., Maas, R., Magid, J., Sutton, M.A., van Grinsven, H., 2011. Developing integrated approaches to nitrogen management. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, pp. 541–550. (Chapter 23).

Reay, D.S., Howard, C.M., Bleeker, A., Higgins, P., Smith, K., Westhoek, H., Rood, T., Theobald, M.R., Sanz Cobeña, A., Rees, R.M., Moran, D., Reis, S., 2011. Societal choice and communicating the European nitrogen challenge. In: Sutton, M.A., Howard, C. M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, Cambridge, pp. 585-601. (Chapter 26).

Reay, D.S., Davidson, E.A., Smith, P., Melillo, J.M., Dentener, F., Crutzen, P.J., 2012. Global agriculture and nitrous oxide emissions. Nat. Climate Change 2, 410–416.

Roy, A., Hammond, L., 2004. Challenges and Opportunities for the Fertilizer Industry. In: Mosier, A.R., Syers, J.K., Freney, J.R. (Eds.), Agriculture and the Nitrogen Cycle. Island Press, Washington, pp. 233–243. (Chapter 17).

Sanz-Cobena, A., Sanchez-Martin, L., Garcia-Torres, L., Vallejo, A., 2012. Gaseous emissions of N_2O and NO and NO_3^- leaching from urea applied with urease and nitrification inhibitors to a maize (*Zea Mays*) crop. Agric., Ecosyst. Environ. 149, 64–73.

Savant, N.K., Stangel, P.J., 1990. Deep placement of urea supergranules in transplanted rice: principles and practices. Fert. Res. 25, 1–85.

Skiba, U., Jone, S., Dragosis, U., Drewer, J., Fowler, D., Rees, R., Pappa, V., Cardenas, L., Chadwick, D., Yamulki, S., 2012. UK emissions of the greenhouse gas nitrous oxide. Philos. Trans. R. Soc. B: Biol. Sci. 367, 1175–1185.

Smith, K.A., Dobbie, K.E., Thorman, R., Watson, C.J., Chadwick, D.R., Yamulki, S., Ball, B.C., 2012. The effect of N fertilizer forms on nitrous oxide emissions from UK arable land and grassland. Nutrient Cycling in Agroecosystems 93, 127–149.

Sutton, M.A., Bleeker, A., 2013. The shape of nitrogen to come. Nature 494, 435–437.

Sutton, M.A., Erisman, J.W., Oenema, O., 2007. Strategies for controlling nitrogen emissions from agriculture: regulatory, voluntary and economic approaches, Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. International Fertilizer Industry Association, Paris245–259 (ISBN:2-9523139-2-X).

Sutton, M.A., Howard, C.M., Bleeker, A., Datta, A., 2013. The global nutrient challenge: from science to public engagement. Environ. Dev. 6, 80–85.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A, Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S., with contributions from Ayyappan, S., Bouwman, A.F., Bustamante, M., Fowler, D., Galloway, J.N., Gavito, M.E., Garnier, J., Greenwood, S., Hellums, D.T., Holland, M., Hoysall, C., Jaramillo, V.J., Klimont, Z., Ometto, J.P., Pathak, H., Plocq Fichelet, V., Powlson, D., Ramakrishna, K., Roy, A., Sanders, K., Sharma, C., Singh, B., Singh, U., Yan, X.Y., Zhang, Y., 2013a. Our Nutrient World: The Challenge to Produce More Food and Energy With Less Pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative, 114 pp.

UN, 2012. The Future We Want. Resolution adopted by the General Assembly on 27 July 2012, A/RES/66/288.

UNEP, 2010. Green Economy Developing Countries Success Stories. United Nations Environment Programme, Geneva.

UNEP, 2011. Towards a Green economy. Pathways to Sustainable Development and Poverty Eradication. United Nations Environment Programme, Nairobi.

Upadhyay, R.K., Patra, D.D., Tewari, S.K., 2011. Natural nitrification inhibitors for higher nitrogen use efficiency, crop yield, and for curtailing global warming. J. Trop. Agric. 49, 19–24.

Van Grinsven, H.J.M., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A., Willems, W.J., 2013. Costs and benefits of nitrogen for Europe and implications for mitigation. Environmental Science & Technology 47, 3571–3579, http://dx.doi.org/10.1021/es303804g.

Winiwarter, W., Höglund-Isaksson, L., Schöpp, W., Tohka, A., Wagner, F., Amann, M., 2010. Emission mitigation potentials and costs for non-CO_2 greenhouse gases in Annex-I countries according to the GAINS model. J. Integrative Environ. Sci. 7, 235–243.

Zaman, M., Blennerhassett, J.D., 2010. Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system. Agric., Ecosyst. Environ. 136, 236–246.

Zaman, M., Zaman, S., Nguyen, M.L., Smith, T.J., Nawaz, S., 2013. Effect of urease and nitrification inhibitors on ammonia and nitrous oxide emissions from simulated urine patches in pastoral system: a two-year study. Sci. Total Environ 469, 97–106. ⟨http://dx.doi.org/10.1016/j.scitotenv.2013.01.014⟩.