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Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions

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Nitrous oxide (N_2O) emissions from agriculture can be tackled by reducing demand for, and consumption of, nitrogen (N) inputs via diet modification and waste reduction, and/or through technologies applied at the field level. Here we focus on the latter options. Opportunities for mitigating N_2O emissions at the field level can be advanced by a clearer scientific understanding of the system complexities leading to emissions, while maintaining agricultural system sustainability and productivity. A range of technologies are available to reduce emissions, but rather than focus specifically on emissions, the broader management and policy focus should be on improved N use efficiency and effectiveness; for lower N_2O emissions per unit of crop and animal product, or per unit of land area.

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Introduction

An estimated 50% more food must be produced by 2050 to meet the needs of nine billion people [1,2]. Unless demand can be reduced through measures such as diet modification or waste reduction, there will be increasing pressure to use more N inputs; potentially increasing N_2O emissions. Using consumption-based measures could reduce pressures on, or moderate growth in, demands for increased N inputs and thereby future N_2O emissions. The impacts measures have been described recently [3–5], so in this article we focus on options to reduce N_2O emissions from agriculture at the field scale.

Increased food production in the past has been made possible, in large part, by the production and use of commercial fertilizer N [6]. A modeling effort has shown the majority of the past increases in atmospheric N_2O could be attributed to fertilizer and manure N inputs [7]. Yet, it is clear that global emissions of greenhouse gases (GHGs) associated with land clearing for extensive agriculture would be far worse if not for the investments in, and adoption of, modern cropping and fertilization technologies. Further, investments in improving crop yields per unit of existing land area, or sustainable agricultural intensification, should be 'prominent among efforts to reduce future GHG emissions' [8]. Such sustainable intensification investments could lead to increased cropping system productivity and can help protect the remaining natural systems from further agricultural encroachment. Improved intensification of management practices (not necessarily greater inputs) may result in more efficient water and fertilizer N use [5,9].

Major cereal grains account for the majority of the global demand for nitrogen (N) inputs from fertilizers and manures. Wheat (*Triticum aestivum* L.) accounts for the largest global consumption of all fertilizer N, followed by maize (*Zea mays* L.), and then rice (*Oryza sativa* L.): 18, 17 and 15%, respectively for the most recently reported calendar year of 2010 [10]. Urea is the dominant fertilizer N source consumed globally, representing 56.5% of fertilizer N consumption in calendar year 2011. Other fertilizer N may be the primary sources in some countries and regions. For example, anhydrous ammonia accounted for 27%, urea ammonium nitrate solutions for 27%, and urea for 22% of the fertilizer N consumed in the U.S. in calendar year 2011. In some major corn-producing U.S. states, anhydrous ammonia and urea each account for 45% of the fertilizer N consumption [11]. Whereas, ammonium nitrate and calcium nitrate accounted for 27–49%, and urea accounted for 5–29% of the fertilizer N consumption in France, Germany, Poland, Spain and the United Kingdom in 2011 (IFA Statistics, International Fertilizer Industry Association, Paris, France, 2014, http://www.fertilizer.org/ifa/HomePage/STATISTICS). Such yearly global statistics are valuable and assembled from country-level statistics. Unfortunately, they do not reflect changes in how these N sources may be managed or modified to nourish crops in fields at regional, provincial, state, county or individual farm levels; nor do they reflect seasonality of consumption at the field-scale [11].

Mitigation challenges: possible options

The in-season uptake and recovery of applied fertilizer N by cereal grain crops (*fertilized crop nitrogen uptake minus unfertilized crop N uptake, divided by the N applied*) in researcher-managed experiments may range from 45% to 65%, while on-farm recoveries are often below 40% [12–14]. Clearly, agriculture has many opportunities to alter in-field management to more efficiently utilize N inputs to reduce N losses that affect direct and indirect N_2O emissions. Some have suggested that N_2O emissions from fertilized croplands could be reduced by more than 50%, through a singular approach of reducing fertilizer N rates, although other management and environmental factors were acknowledged as also influencing emissions [15]. It is well recognized that the highest crop N use efficiency (NUE; i.e. plant recovery of applied N) is usually achieved with the lowest increment of N input [12], but it would be reprehensible and impractical to strive to increase NUE by limiting N inputs to only the lowest rates. Such action would greatly jeopardize sustainable food production. The grand challenge is how to improve NUE that leads to reduced N_2O emissions, while also achieving greater N *effectiveness* in crop and livestock production (i.e. more food output per unit N input) [16•]. Among the largest obstacles in attaining lower agricultural N_2O emissions is the recognition by farmers and their advisers that direct N_2O-N losses, on average, are often equivalent to $\leq$1% of the N applied [17]; [*default Tier 1 IPCC emission factor*]. For example, if one assumes a nominal application rate of 170 kg of N/ha for a high-yielding (e.g. 10 Mg/ha) maize (*Zea mays* L.) crop (*average rate of N applied to all corn hectares in the U.S. in 2010 was 156 kg/ha*), the loss of 1.7 kg of N/ha/yr as N_2O amounts to a cost of less than one U.S. dollar per hectare; a relatively small economic loss in most current farm enterprise budgets. Even with well-calibrated, conventional spinner spreaders, it is unlikely that most farmers could apply fertilizer inputs with greater accuracy than ±5–10% of the desired rate [18,19]. In addition to these important socio-economic and physical challenges, it is being increasingly recognized that there is no single management change that can bring about both increased crop productivity and reduced N_2O emissions equally well across broad geographies [20]. While site-to-site variability and climate effects on N_2O emissions are large, site-specific changes in agricultural management practices can provide solutions and should receive greater attention [21].

To gain greater farmer interest in, and adoption of, management changes that will present the greatest probability of reducing both direct and indirect N_2O emissions, it will be necessary to more broadly focus on management practices which simultaneously lead to greater NUE and effectiveness. Greater implementation and adaptation of practices to improve crop and cropping system N recovery, soil N retention, and reduced field losses of reactive N via the other prominent pathways are needed. Site-specific management changes and adoption of technologies that will help minimize losses of N via ammonia volatilization, and nitrate runoff, leaching, and drainage pathways may garner greater agricultural attention. Such losses often represent greater economic loss to the farmer than direct N_2O emissions (although denitrification loss as N_2 may also represent an economic concern). The need for site-specific management efforts in agriculture to enhance crop and soil recovery of applied N (efficiency), enhance crop productivity per unit of N applied (effectiveness), and reduce N_2O per unit of crop output have been emphasized [22–25,26•,27,28•]. Cropping system NUE improvements at modest fertilizer N rates have correlated strongly with reduced N_2O emissions, as reported for 19 studies by Van Groenigen *et al.* [25]. Briefly, we draw attention to some recent research advances in management practices and technology tools to help expand our understanding about soil, crop, and livestock systems management for enhanced NUE and N_2O emission mitigation.

4R nutrient management

Robertson and Vitousek [20] stated that 'Mismatched timing of N availability with crop need is probably the single greatest contributor to excess N loss in annual cropping systems.' The global fertilizer industry has developed, and is supporting, a 4R Nutrient Stewardship initiative [29] which is based on the principles of using the right nutrient source, at the right rate, right time, and in the right place to achieve the basic economic, social, and environmental elements of sustainability. Optimizing site-specific 4R Best Management Practices (BMPs) 'depends on important roles played by many partners including farmers, crop advisers, scientists, policymakers, consumers, and the general public' [30], and should be sensitive to local agronomic, economic, and environmental challenges. These industry-led 4R nutrient use efficiency and effectiveness education and implementation efforts are congruent with needed emphases on 'just enough' N and NUE. Advances in N science and agricultural policy were the focus of recent conferences in the USA (Improving Nitrogen Use Efficiency in Crop and Livestock Production Systems: Existing Technical, Economic, and Social Impediments and Future Opportunities, Soil Science Society of America, August 2013, http://nitrogennorthamerica.org/NUE-KansasCity2013.html) and Uganda (6th International Nitrogen Conference, International Nitrogen Initiative October 2013, http://n2013.org/#). Flynn and Smith [31] provided an excellent review of crop, soil, and nutrient management N_2O emission mitigation options, with emphasis on 4R nutrient management principles.

Emission mitigation options and costs for crop farmers, including changes in the source, rate, time, and place of N application (4R), were highlighted in a USDA report published in early 2013 [32]. Some mitigation options, in some geographies, may be as straightforward as switching conventional N sources (from anhydrous ammonia to urea), which could result in >50% reduction in annual N_2O emissions [33].

Management actions to mitigate N_2O losses must be balanced with consideration of all major N loss pathways, since tradeoffs in N losses could occur. Even qualitative estimates of likely tradeoffs among various leaching and gaseous losses of N in response to fertilizer management options are complex, preliminary, and controversial [24,34].

Enhanced efficiency fertilizers

In the last 5–10 years, there has been increased research into, and farmer adoption of, enhanced efficiency nitrogen fertilizers (EENFs, or EEFs for simplicity here). These EEFs are defined by the Association of American Plant Food Control Officials (AAPFCO) as 'fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment (e.g. gaseous losses, leaching, or runoff) when compared to an appropriate reference product' [35]. Such reference products are 'soluble fertilizer products (before treatment by reaction, coating, encapsulation, addition of inhibitors, compaction, occlusion, or by other means) or the corresponding product used for comparison to substantiate enhanced efficiency claims'. Table 1 summarizes recent examples of N_2O emission reductions with EEFs and changes in the source, time and place of N application. Site-specific conditions (e.g. soil texture, moisture content, oxygen status, temperature, pH, organic matter) affect not only direct N_2O emissions, but also ammonia emissions and other N losses that contribute to indirect N_2O emissions [44–46,47••,48].

In summarizing recent research with EEFs in the U.S., Hatfield and Venterea [47••] observed that a single N rate was used in many studies when comparing EEF N to reference fertilizer products. Future EEF studies should involve a range of N rates to better define optimum N rate and source combinations. A meta-analysis of data from 48 studies (548 observations) conducted before 2012 in the major corn-producing areas of the U.S. and southern Canada showed that use of the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) in combination with the nitrification inhibitor dicyandiamide (DCD) was the only N management strategy that consistently reduced N_2O emissions [42]. That meta-analysis showed that N_2O emission responses to N rate varied by land resource regions, indicating the need for region-specific approaches and management strategies. For example, polymer-coated urea (PCU) products have been effective in mitigating N_2O in some studies [35,44,45] but not others [27,39,43].

Total N uptake in New Zealand pastures was increased >20%, and nitrate leaching and N_2O emissions were reduced >80 and >30%, respectively, when both urease and nitrification inhibitors were added to urea [38]. Yet, ammonia emissions were increased >30% when both inhibitors were added to urea. There are few other published reports on nutrient management practices that reduce N_2O emissions while simultaneously reducing other environmental N losses.

Increasing N rates may increase N_2O emissions, but not appreciably so in many cases unless the agronomically optimum N rate is significantly exceeded, resulting in 'surplus' N supply [24] [(citing Bouwman *et al.*, 2002)] [25,27]. Hoben *et al.* [49] stated, 'decreasing excess N additions and soil N surpluses in cropping systems that receive N fertilizer may be the most effective and achievable GHG mitigation option for agriculture'. It is commonly perceived that farmers may apply more N than actually needed to meet crop uptake demands, in countering the losses of N from the soil, crop and applied N. Yet, Snyder [50] found that, on average, corn growers in the seven leading corn-producing states in the U.S. applied N at rates closer to the Land Grant University research-based recommendations from 2000 to 2010 (approximately 6 kg of N/ha lower than the recommended). However, as Ribaudo *et al.* [51] reported, 31% of all U.S. corn hectares from 2001 to 2010 may have received 'excess' N. These two reports reflect trends toward improved U.S. corn system management, which may include adoption of EEFs, but also indicate many remaining opportunities to improve N management.

Nitrogen sensors and variable rate application

An increasing number of farmers and crop advisers around the world have access to global positioning system (GPS) resources and geographic information systems (GIS). Coupling these tools with decision support systems, application equipment technologies, and certain N sources may make it increasingly possible to better match N rates and times of application which are sensitive to in-season crop N demands. The goal of N sensor technology is not to reduce N rates, but to enable better matching of crop N needs, with in-season sensitivity that leads to improved N use efficiency and greater farmer profitability. Field-scale studies at 16 sites in Missouri (USA) showed that N sensor-based applications and use of adjacent N-rich reference strips could potentially save farmers 10–50 kg of N/ha in N rates on corn [52]. Previous on-farm research in Missouri showed that use of improved N rate technologies resulted in >27% reductions in residual soil nitrate [53]. On-farm, sensor-based N studies in 15 wheat fields in Oklahoma (USA) showed an average savings of 20 kg of N/ha, and resulted in a N rate

Table 1

Recent examples of N_2O emission reductions achieved with contrasting nitrogen fertilizer source, time, and placement[a]

Fertilizer technology or nitrogen management comparisons	Emission reduction[b] (%)	Field study information	Reference
Urease inhibitor (UI) versus no inhibitor	Nil	Meta analysis; 35 studies[c]	[36]
Nitrification inhibitor (NI) or polymer coated urea (PCU) versus conventional fertilizer	35–38		
Variety of changes in source, time, place of application versus standard or reference practices	20–80	Summary of >20 studies[c]	[37]
Depth of fertilizer placement, combined with reduced tillage; >5 cm versus <5 cm	>30	Meta analysis; 239 comparisons, including years in no-till or reduced tillage[d]	[26•]
Urea with UI and NI versus urea with no inhibitor	37	Dairy cows excluded 2 months prior; other N losses measured; plant N recovery ranged from 50 to 85% of applied N[e]	[38]
Urea with UI versus urea with no inhibitor	5		
Diammonium phosphate (DAP) versus urea with phosphate	8		
DAP versus urea with phosphate plus elemental sulfur	19		
Urea versus anhydrous ammonia	50	Full growing season N_2O measurements; continuous corn compared with corn-soybean systems in place >15 years[f]	[33]
Fertilizer N (including urea with UI and NI inhibitor, urea–ammonium nitrate (UAN) with UI and NI, urea, UAN, ammonium nitrate, or PCU) versus poultry litter	46–81	Full growing season N_2O measurements; non-irrigated; humid region; surface broadcast N application, no incorporation[f]	[39]
Manure (poultry, or liquid swine or liquid dairy) versus calcium ammonium nitrate	Nil	Surface applied N in spring to silty clay soil; treatments incorporated by tillage on day of application[f]	[40]
Calcium ammonium nitrate versus manure (poultry, or liquid swine or liquid dairy)	54	Surface applied N in spring to sandy loam soil; treatments incorporated by tillage on day of application[f]	
Liquid swine or dairy manure versus solid poultry manure	41	Surface applied N in spring to sandy loam soil; treatments incorporated by tillage on day of application; poultry manure pH 8.8, high carbon content[f]	
UAN with nitrification inhibitor versus UAN	19–67	Weekly to bi-weekly N_2O measurements during growing season; side-dressed, subsurface colter-applied UAN at V4 to V6 growth stage[f]	[41]
Urea with UI and NI versus urea with no inhibitor	46	Full growing season N_2O measurements; irrigated; no-till and tilled; surface banded N near emerged corn rows[f]	[35]
UAN with UI and NI versus UAN with no inhibitor	21		
PCU versus urea	42		
PCU versus UAN	14		
UAN with UI and NI versus urea with no inhibitor	61		
UAN with UI and NI versus UAN with no inhibitor	41		
UAN versus urea	35		
UAN with soluble methylene ureas and urea triazones versus urea	57		
UAN with soluble methylene ureas and urea triazones versus UAN	28		
Fertilizers with UI and NI versus fertilizers with no inhibitors	38	Meta analysis; 3 studies, 20 observations[f]	[42]
Commercial fertilizer versus manure	40	Meta analysis; 9 studies, 73 observations[f]	
Urea with NI versus urea with no inhibitor	81–100	Full growing season N_2O measurements (217–382 days); two consecutive ratoon crops; plant residue removed or burned fertilizer banded >5 cm deep, 20 cm from sugarcane row; clay loam soil[g]	[43]
Polymer sulfur coated urea (PSCU)	−35 to −46		

[a] Note that emissions reductions with these practices are sometimes not achieved. See Ref. [28•] for discussion of site-specific limitations.

[b] Mean or range of reduction in N_2O emissions achieved with mitigating practice (listed first) relative to reference practice (listed second).

[c] Using a range of agricultural crops.

[d] Using a range of agricultural crops excluding rice (*Oryza sativa* L.).

[e] Using perennial ryegrass (*Lolium perenne L.*)/white clover (*Trifolium repens L.*) pasture.

[f] Using corn (*Zea mays L.*).

[g] Using sugarcane (*Saccharum officinarum* L.).

application lower than the Farmer Practice 60% of the time, and a higher application 40% of the time [54].

Deployment of similar precision N technologies in commercial 'Valencia' orange production in Florida (USA) helped protect water resources and improve crop tree N uptake efficiency. Optical sensors were used to measure tree size and to adjust N rates on-the-go (variable rate), which resulted in 40% less fertilizer N use, >60% less nitrate leaching, and improved citrus production profitability [55].

Agricultural retailer use of N-sensors and variable rate fertilization in the U.S. was reported in the 2013 precision agriculture survey by CropLife and Purdue University (https://www.agecon.purdue.edu/cab/ArticlesDatabase/articles/2013PrecisionAgSurvey.pdf). Retailer use of crop N-sensors (chlorophyll/greenness sensors) rose from 4% in 2011 to 7% in 2013. More than 51% of those survey respondents use controller-driven, single-product, variable-rate fertilizer application; 47% provide multi-nutrient variable-rate application to their customers. Although a similar survey has not been formally conducted in western Europe, the Yara N-Sensor$^{\mathrm{TM}}$ is being used on >1.2 million hectares of the total 104 million cropland hectares in the EU-27 (J. Jasper, personal communication, 6 February 2014). The skill sets needed to use these technologies, their costs, and their relatively unknown range in economic returns to farmers, make them promising tools with a somewhat uncertain future. The potential for placing N-sensing capabilities in more economical unmanned aerial vehicles (UAVs), raises the prospects for improved N use efficiency through increased adoption of in-season crop N nutrition monitoring and N fertilization. In the U.S., use of UAVs is subject to approval of the Federal Aviation Administration, but is currently being tested at several sites (http://www.faa.gov/about/initiatives/uas/).

Asynchronous timing of N availability with crop needs was cited as probably 'the single greatest contributor to excess N loss in annual cropping systems' [20]. However, achieving synchrony in N supply may not always reduce annual cumulative N_2O emissions ([28•]; R Venterea, and J Baker, Abstract 162-7, Annual Meetings of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 3-6 November 2013, Tampa, Florida, USA, https://scisoc.confex.com/scisoc/2013am/webprogram/Paper78779.html). Instead, management practices that influence the rate of nitrification, and especially soil nitrite accumulation, may be most likely to reduce N_2O emissions [56].

Cover crops

Winter cover crops (catch crops or green manures) can help protect soil from erosion, improve soil carbon levels, and also aid in the capture and retention of residual inorganic N; especially nitrate present following spring and summer crops [57]. Yet, there are indications that in some soils, cover crops may *stimulate* (i.e. increase) N_2O emissions possibly because of the release of labile carbon and N from cover crop residues. The method of irrigation, soil moisture regime, whether the cover crop is a cereal or a legume, and presence or absence of past fertilizer bands may affect the degree to which cover crops may stimulate N_2O emissions [58–61]. For example, no corresponding reductions in N_2O emissions from inclusion of catch crops or a grass-clover ley were found in contrasting conventional and organic winter wheat cropping systems studies [62]. Cover crops may confer a 'tightening' of the cropping system N cycle, may potentially reduce manure and fertilizer N inputs, and potentially lower cumulative N_2O emissions risks. Such reduced emissions potential will depend on conferred changes in soil porosity, water retention, soil oxygen status, soil temperature, and organic matter N mineralization dynamics.

No-till and reduced till

The review by Snyder *et al.* [24] indicated that no-till and reduced tillage effects on N_2O emissions have varied, with lower emissions from no-till compared to a tilled system in a semi-arid, irrigated corn system in Colorado, USA. Mixed results occurred with nonirrigated corn in Minnesota (USA), depending on the N source and/or place of application [63]. Rochette *et al.* [64] found that no-till reduced N_2O emissions in silt loam soils, but in soils with a higher clay content, no-till resulted in increased emissions compared to conventional tillage. Halvorson *et al.* [45] found that N_2O emissions were lower with no-till compared to a tilled, irrigated corn system, and greater N_2O emission reduction benefits with EEFs were achieved under no-till. Van Kessel *et al.* [26•] observed that no-till or reduced tillage management can increase N_2O emissions in the short term, especially in drier climates, but after 10 or more years, no-till and reduced tillage may result in decreased N_2O emissions relative to tilled management. Their meta-analysis also found that reduced tillage systems emitted less N_2O than conventional tillage when N was placed deeper than 5 cm [26].

Biochar

Soil incorporation of biochar at rates >15–30 t/ha has reduced N_2O emissions >37% [65–67], but the mechanisms by which biochar may affect N_2O emissions and the economics are not well understood.

Livestock management

Only brief highlights for enhanced N_2O emissions mitigation in livestock production are possible here. It is well known that the majority of N inputs to agriculture in many developed countries are for the purpose of feed production, to provide protein-sufficient diets to livestock [68]. One of the most promising ways for many livestock growers to enhance NUE is to more optimally manage dietary crude protein. The bulk of the excreted N by ruminants is in the urine, while in swine it is in both urine and feces. In poultry, the feces contain uric acid, which mineralizes to urea [69]. Farmers and dairy nutrition consultants can monitor milk urea N concentrations of lactating dairy cows, make adjustments in crude protein levels in the diets to match animal nutritional requirements, and significantly reduce ammonia and N_2O emissions [70•]. Proper manure N crediting and optimal stocking rates on pastures, and inclusion of leguminous forages (which biologically fix N), can potentially raise whole farm N use efficiency from <30% to near 65% for better farm profits and reduced N losses [22]. Failure to consider the correct mineral fertilizer equivalent (MFE) of manure may aggravate N losses, including N_2O emissions [71]. The European Union established the Nitrate Directive in 1991 (Council Directive 91/676/EEC; http://ec.europa.eu/environment/water/water-nitrates/index_en.html) to help address the potential for over-application of manure and supplemental fertilizer N.

Slurry or liquid manure systems, as opposed to straw or deep litter systems, were suggested as presenting sizeable opportunities to reduce N_2O emissions in animal production. The anaerobic nature of liquid systems limits nitrification/denitrification processes [72••]. Subsurface placement of liquid manures can substantially reduce ammonia emissions [73]. Use of a subsurface broiler litter (i.e. dry manure plus litter) applicator can reduce N losses by both ammonia volatilization and surface runoff (as ammonium and total Kjeldahl N) by >95% [74]. Adding liquid aluminum chloride to poultry bedding (e.g. rice hulls) can help reduce ammonia volatilization, chiefly by reducing the pH of the litter [75].

Montes *et al.* [76] stated, 'Incorporating manures can greatly reduce NH_3 emissions, leaving more N susceptible to emission as N_2O through nitrification and denitrification. However, reduction in NH_3 losses with incorporation means that a smaller quantity of manure is required to provide the crop N requirements, and therefore the potential for N_2O production is reduced'. Field studies comparing surface application and subsurface-banded manure application indicated higher N_2O emissions with subsurface banding [73]. Tradeoffs or 'pollution swapping' among reductions in ammonia emissions, reductions in leaching/runoff/drainage losses of nitrate, and risks for elevated N_2O emissions [24,34,37] are frequently mentioned in the literature. Such emission tradeoffs should not be allowed to compromise advice on reducing emissions of NH_3 [77], since indirect N_2O losses associated with nitrate leaching and ammonia volatilization can sometimes be larger than direct N_2O losses [78]. Unfortunately, reports of simultaneous measurements of these N losses from fields or small watersheds are few. 'Further environmental and agricultural economic analysis of potentially greater N_2O emissions with manure injection is needed to assess the full environmental cost and the potential economic liability to farmers' [73].

Relative feed grain-to-meat conversions of animal production systems rank in the following order, may represent varied N use efficiencies, and potentially enhanced N_2O emission mitigation: fish > poultry > swine > sheep > cattle [79,80]. Shifts toward a greater human dietary preference for vegetables over meat may also alter N consumption patterns and contribute to sizeable gains of N efficiency within the food chain [81,82].

Increased NUE in animal production will require site-specific, targeted combinations of animal breeding, improvements in feed quality and feed management, and improvements in animal management; and if fully implemented could lead to an estimated 10–30% reduction in excreted N per animal. As with improvements in cropping system N use efficiency, there is a great need for 'more education, training, demonstration, and development' [16•].

Conclusions

Application of demand-side measures (e.g. dietary choices, reduction in food wastage, policy instruments), and implementation of the field level technologies described above, may make it possible to more sustainably nourish more people in the future with fewer N_2O emissions. An emphasis on increased crop and animal outputs per unit of N input should be encouraged to help to mitigate N_2O emissions, and to further protect natural areas. Mitigation research, education, and supportive policies should not overlook the need to also improve the sustainable use of other essential nutrients, water, and crop and livestock protection inputs because they also affect NUE. Cross-disciplinary (economics, ecology, soil science) research/outreach may help improve farmer 4R BMP adoption and NUE.

Competing financial interests

None.

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