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Efficient use of reactive nitrogen for productive agroecosystems

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The growing world population needs reactive nitrogen (N) for secure production of food, fibre and, increasingly, energy. This special issue addresses the low use efficiency of reactive N, that both represents a cost to farms, and leads to N losses that degrade surface, ground and coastal waters, increase greenhouse gases and atmospheric pollution, and reduce biodiversity. The need for balanced N inputs is increasingly recognised globally and is directly connected to six of the 17 United Nations Global Sustainable Development Goals (Table 1) that were endorsed, in a 2015 meeting of world leaders, to be a guiding framework for countries to develop national roadmaps towards sustainable development (Dobermann 2016).

The global challenge of balancing the positive and negative impacts of reactive N has been addressed at conferences of the International Nitrogen Initiative (INI), held at about three-year intervals (Erisman 2016). The seventh and most recent conference, INI2016, was held in Melbourne in December 2016 with the theme 'Solutions to enhance nitrogen efficiency for the world'. The 256 papers presented at the conference are available at www.ini2016.com.

The 20 papers in this special issue of Soil Research were selected from the general submissions and plenary invitations made during the INI2016 conference. These discuss N management in diverse agroecosystems across the globe. While many papers address N-use efficiency in contrasting agricultural systems, Galloway *et al*. (2017) promote the benefits of reducing excess protein consumption and identify environmental and health benefits of a diet in which all humans consume an adequate but not excessive quantity of protein. They propose calculating a 'N footprint' at a personal, regional or national level as a means of highlighting disparities in N consumption.

Nitrogen fertiliser use has grown steadily since the 1950s, transforming agriculture and food production in most parts of the world. The efficiency of N use can be improved in many regions by applying the '4R principles', the right fertiliser type, at the right time, in the right place and at the right amount (Snyder 2017). Even where N fertiliser is on average used sparingly, such as in sub-Saharan Africa, there is a paradox of insufficient N use causing low crop yield and human malnutrition, as well as excessive N contributing to eutrophication of iconic water bodies (Masso *et al*. 2017). Policies to support resource-poor farmers, in combination with extension of the good agronomic practices associated with integrated soil fertility management are needed in this region (Masso *et al*. 2017).

The variation in N management is shown by the contrast between dryland cereals and intensive agriculture in irrigated and high-rainfall regions globally. For example, N fertiliser inputs for Australian dryland wheat are small by world standards and N-use efficiency is relatively low (Angus and Grace 2017). About 40% of this wheat is produced on light-textured-soils where high rainfall can lead to leaching losses (Duncan *et al*. 2017). Increased N fertiliser inputs will be

Table 1. Sustainable development goals of the United Nations and the contributions of reactive N to human welfare and solving environmental problems

	Development goal	Connection with N
1	No poverty	
2	Zero hunger	✓
3	Good health and wellbeing	
4	Quality education	
5	Gender equality	
6	Clean water and sanitation	✓
7	Affordable and clean energy	
8	Decent work and economic growth	
9	Industry, innovation and infrastructure	
10	Reduced inequalities	
11	Sustainable cities and communities	
12	Responsible consumption and production	✓
13	Climate action	✓
14	Life below water	✓
15	Life on land	✓
16	Peace, justice and strong institutions	
17	Partnerships for the goals	

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required to maintain grain protein concentration under future elevated carbon dioxide conditions (Walker *et al*. 2017). In contrast, high-value cropping systems in irrigated and high-rainfall environments, such as sugarcane in the wet tropics (Angus and Grace 2017), vegetables (Porter *et al*. 2017), rice (Rose *et al*. 2017) and dairy production (Aarons *et al*. 2017; Gourley *et al*. 2017), all have large N fertiliser inputs, low N-use efficiencies and large losses. A similar pattern of increasing N fertiliser inputs and large N losses is reported in China where production of rice occupies 30% of the crop-producing land and consumes an estimated 15 million tonnes of fertiliser (Yang *et al*. 2017).

Intensive animal production is a major source of N loss to the environment because N-use efficiency is low and there are large inputs of reactive N from fertiliser, imported feed and biological N-fixation, encouraged by the high profitability of producing animal protein. As demand for animal protein continues to rise, a growing global issue is managing excreted N and land application of animal manure (Liu *et al*. 2017). In China, modelling by Li *et al*. (2017) shows that manure was a major contributor to N pollution in rivers and coastal water bodies and that improved manure recycling to crops has the potential to improve water quality. Improved predictions of reactive N availability from land application of animal manure have also been shown to reduce additional N fertiliser inputs and improve crop N-use efficiency (Sørenson *et al*. 2017). This is particularly challenging for some animal production systems such as dairying, where the complexity of N cycling requires comprehensive methods to assessing N-use efficiency in combination with high productivity (de Klein *et al*. 2017). For example, in grazing systems dietary N is often greater than animal requirements, leading to high concentrations of N in excreta and excessive inputs where animals spend extended periods (Aarons *et al*. 2017).

Nitrogen immobilisation, mineralisation and soil microbes responsible for N turnover influence plant N uptake, particularly in response to the presence of crop residues and to a previous legume crop (Peoples *et al*. 2017; Toda and Uchida 2017). Peoples *et al*. (2017) reviewed 16 cropping experiments undertaken between 1989 and 2016 showing that legume pre-crops boosted soil mineral N concentrations more than non-legumes, and brown-manured legumes contributed more than grain legumes. Angus and Grace (2017) suggest that placing N fertiliser in mid-row bands may limit the immobilisation of fertiliser N and favour crop roots in their competition with immobilising microbes. Fertiliser placement systems that reduce the release of nitrate in the topsoil could reduce denitrification and nitrate leaching losses.

Enhanced efficiency fertilisers (EEF) are products with coatings or with the addition of urease or nitrification inhibitors that may improve crop N-use efficiency (Snyder 2017). Many papers at INI2016 reported the use of EEF to mitigate environmental N losses to surface and groundwater, and gaseous emissions of ammonia and nitrous oxide (N_2O) to the atmosphere. However, the wide range of responses to EEF in crop yields, N recovery and N loss highlight the need for targeted and site-specific use. For example, in an experiment with high-input irrigated vegetables fertilised with poultry manure and synthetic N fertilisers, N_2O losses were amongst the highest recorded for Australian crops (Porter *et al*. 2017). However, incorporating the manure and applying a nitrification inhibitor reduced the cumulative N_2O emissions by 76%. In a dryland wheat experiment, the use of a nitrification inhibitor slowed nitrification in a range of soils and increased yield by approximately 10%, but this was associated with specific soil conditions (Duncan *et al*. 2017). In aerobic rice crops in the subtropics, Rose *et al*. (2017) found that the nitrification inhibitor DMPP lowered N_2O emissions during peak flux events but not over the entire season.

The relative price of N fertiliser compared with agricultural products also affects N-use efficiencies (Angus and Grace 2017; Liu *et al.* 2017; Masso *et al*. 2017; Pannell 2017). In particular, agricultural subsidies, either to reduce the price of N fertiliser or increase the price of farm products drive overuse of N fertiliser. The obvious link between subsidies, N fertiliser overuse and the accumulation of N in soil, water and the atmosphere has been apparent for at least 30 years (Cottrell 1987). It is therefore surprising that the subject of reducing subsidies has not received more recent attention as a path to reducing N pollution. For example in the European Nitrogen Assessment, only one chapter deals with the relationship between the N : grain price ratio and fertiliser usage (Jensen and Schjoerring 2011). In sub-Saharan Africa, implementing policies to improve the quality of inputs, outputs and supply chain infrastructure, and reduce input costs, is expected to increase agronomic N efficiency (Masso *et al*. 2017).

Delegates to the Melbourne INI2106 conference helped prepare international comparisons of the ratios of farm-gate prices of N fertiliser and grain price ratios at the time of the conference. These are shown in detail in the Supplementary Information but are summarised as follows. In the USA, Australia and parts of Africa the price ratio was between ~4 and 6, indicating that neither N fertiliser nor grain was subsidised. For one location in Western Europe the price ratio was 2.3, suggesting that there was subsidy, probably on grain. For India and China the price ratio was particularly low (0.9–1.5) because the price of N fertiliser is subsidised. At these price ratios, farmers would find it profitable to apply N fertiliser at such high rates that there is little additional assimilation by crops, little additional production and large losses to the environment.

Many solutions to improve N-use efficiency were presented by delegates at the conference; a selection of which are described in this special issue. The use of EEFs to minimise N losses and improve crop yields was shown for various production systems although further research to identify site-specific factors is recommended (Duncan *et al*. 2017; Porter *et al*. 2017; Rose *et al*. 2017). Aarons *et al*. (2017) recommend a method to quantify N excretion by grazing dairy cows, which in conjunction with estimates of the time animals spend in locations on farm can improve N management. Incorporating animal manures in soil reduces N losses (Li *et al*. 2017; Porter *et al*. 2017; Sørenson *et al*. 2017). Decision support tools can improve N fertiliser recommendations for pasture (Gourley *et al*. 2017), subtropical grain (Herridge 2017) and rice (Yang *et al*. 2017) production systems, while more simple relationships can make similar improvements for cereals grown after grain legume crops (Peoples *et al*. 2017).

Delegates at several INI conferences have developed consensus Declarations to draw the attention of governments and civil society to the increasing global dependence on reactive N for production of food and fibre, and the environmental damage that often accompanies its overuse. The Melbourne Declaration on 'Responsible Nitrogen Management for a Sustainable Future' is available at www.ini.com/declaration. In keeping with the UN Sustainable Developmental Goals, the declaration recommended that government policies on N management must be based on sound science. The declaration also recognised that that all peoples of the world are entitled to adequate nutritional and living standards and that N management should strive to provide them with the productivity benefits of reactive N while minimising its damage to the environment. All the world community is part of the problem and also part of the solution, whether as consumers of protein or users of reactive N. Making improvements requires sustained support for science and technology related to N management in agriculture, industry, transport and energy production. This should include globally harmonised performance indicators that reflect productivity, economic efficiency and environmental sustainability. Uniquely the declaration draws attention to farm-level economics associated with N fertiliser use and the simple but important observation that N fertiliser is overused when it is cheap relative to the product. The subsidies that encourage overuse would better be spent on research, development and extension to improve N-use efficiency at high levels of productivity.

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Supplementary information

Farm-gate prices of fertiliser N and grain, and the N : grain price ratios for selected cropping regions in late 2016

Region	Farm-gate N price t^{-1}	Farm-gate grain price t^{-1}	Grain product	N : grain price ratio
Ethiopia	ET Birr 24 347	ET Birr 4150	Maize	5.9
Ghana	Cedi 3478	Cedi 900	Maize	3.9
Kenya	Ksh 139 130	Ksh 33 333	Maize	4.2
Australia (Stockinbingal)	$AU 935	$AU 180	Wheat (APW)	5.2
China (six counties in Jiangsu)	$US 526	$US 330	Wheat	1.6
Europe (southern Sweden)	SEK 2782	SEK1280	Milling wheat	2.2
India (Andhra Pradesh)	Rupee 11 950	Rupee 13 250	Rice	0.9
USA (Illinois)	$US 729	$US 135	Wheat	5.4
USA (Montana)	$US 748	$US 170	Wheat (HRS)	4.4