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REVIEW

SUSTAINABLE NITROGEN MANAGEMENT IN AUSTRALIAN AGROECOSYSTEMS: CHALLENGES AND OPPORTUNITIES

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KEYWORDS

Australian agroecosystems, reactive nitrogen, sustainable development

HIGHLIGHTS

- There is huge potential for improvement of nitrogen management in Australia.
- N management should incorporate environmental, social and economic sustainability.
- Agronomic, ecological and socioeconomic approaches and efforts are needed.

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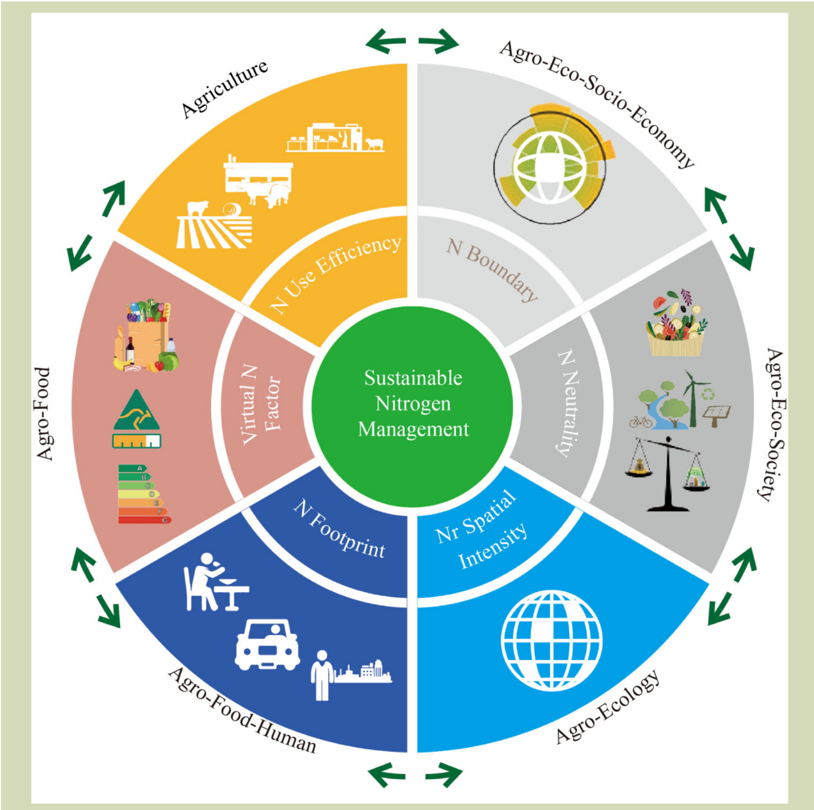
GRAPHICAL ABSTRACT



ABSTRACT

Nitrogen is an essential nutrient that supports life, but excess N in the human-environment system causes multiple adverse effects from the local to the global scale. Sustainable N management in agroecosystems, therefore, has become more and more critical to address the increasing concern over food security, environmental quality and climate change. Australia is facing a serious challenge for sustainable N management due to its emission-intensive lifestyle (high level of animal-source foods and fossil fuels consumption) and its diversity of agricultural production systems, from extensive rainfed grain systems with mining of soil N to intensive crop and animal production systems with excessive use of N. This paper reviews the major challenges and future opportunities for making Australian agrifood systems more sustainable, less polluting and more profitable.

1 REACTIVE NITROGEN CREATION

Nitrogen is an essential component of nucleic acids and enzyme proteins found in living cells within plants, animals and humans. Although the element N is extremely abundant and makes up 78% of the total volume of the Earth's atmosphere, this huge reservoir of N exists mainly as non-reactive N_2 which is not biologically available to most organisms. By natural mechanisms, the creation of reactive N (Nr; all species of N except N_2) from N_2 is primarily through biological N fixation (BNF), lightning and biomass combustion. By anthropogenic activities, the creation of Nr from N_2 is primarily through the Haber-Bosch process, combustion of fossil fuels, and cultivation of legumes, rice, and other crops that promote BNF[1]. Until the invention of the Haber-Bosch process in the early 1900s, limited availability of naturally created Nr severely constrained both agricultural and industrial productivity. The Haber-Bosch process makes large-scale chemical production of Nr economically viable and has since boosted the production of many industrial compounds like dyes and artificial fibers, with the greatest impact on the production of explosives and fertilizers[2].

2 BENEFITS AND UNINTENDED CONSEQUENCES OF REACTIVE NITROGEN

One hundred years on we live in a world transformed by, and highly dependent upon, Haber-Bosch Nr[3]. Of the total Nr manufactured by the Haber-Bosch process, around 80% is used in the production of agricultural fertilizers. These fertilizers have dramatically increased global agricultural productivity and now feed around half of humanity[3,4]. In 1908, 1 ha of arable land could only support 1.9 people but this increased to 4.3 people by 2008[3]. The remaining 20% of Nr manufactured by the Haber-Bosch process has been used in industrial products (e.g., nylon and explosives). From 1960 to 2008, the global industrial Nr flux has increased rapidly from 2.5 to 25.4 $Tg \cdot yr^{-1}$ N[5].

Although the essential role of Nr in agricultural and industrial production is undeniable, the unintended consequences of excessive Nr inputs have been seen in the present-day environment across multiple scales. Nr forms include inorganic reduced forms of N (e.g., ammonia and ammonium), inorganic oxidized forms of N (e.g., nitrogen oxides, nitric acid, nitrous oxide and nitrate), and organic compounds (e.g., urea, amines, proteins and nucleic acids). Nr species can be interconverted and the same atom of Nr can cause multiple effects in the Earth's atmosphere, hydrosphere and biosphere, and on human health, with a wide variety of consequences[6]. In the atmosphere, Nr gives rise to smog, causes stratospheric ozone depletion, and enhances the greenhouse effect. In terrestrial ecosystems, Nr leads to soil acidification, forest dieback, and biodiversity loss. In marine and freshwater ecosystems, Nr contributes to groundwater pollution, ocean acidification and eutrophication, which are related to algal blooms and biodiversity loss[7]. In human society, the high levels of Nr in water and air have been directly and indirectly connected with human ailments, diseases and allergies (e.g., $PM_{2.5}$, inhalable particles $\leqslant$ 2.5 μm). This Nr-related damage to environmental and human health in the EU has been estimated at 75 billion to 485 billion $EUR \cdot yr^{-1}$[8].

3 CHALLENGES FOR SUSTAINABLE N MANAGEMENT IN AUSTRALIA

Globally, there is an uneven distribution of N resources and a huge disparity in N management practices. In areas where N resources and technologies are limited, like sub-Saharan Africa, most of the N added to croplands is converted to crop products with little lost as pollution but also with limited yield. In regions that have high N fertilization inputs but inadequate technologies and management practices, such as China, excessive N input is lost to the environment, causing air and water pollution and may have a negative impact on crop yield. Countries like the USA, have favorable environmental conditions, N resources, advanced technologies and management practices, a high percentage of added N is converted to crop products even at relatively high N input rates. Australia faces similar N issues to other countries, but has its own unique challenges in sustainable N management due to both soil N mining in rainfed grain production systems (too-little N issue like sub-Saharan Africa) and to excessive use of N in intensive crop and animal production systems (e.g., vegetables, cash crops, and dairy and beef feedlots) (too-much N issue like China)[9,10]. Like the USA, Australia also has adequate N resources, advanced technologies and management practices, demonstrating the huge potential for improvement and sustainable N management in Australia.

Meanwhile, a report by the UN Sustainable Development Solutions Network ranked Australia 38th of 162 countries in terms of progress toward achieving the sustainable development goals (SDGs), which is lower than most other Organization for Economic Cooperation and Development nations. Australia suffered its worst result on SDG 12 (responsible consumption and production) and SDG 13 (climate action), highlighting the need for major transformations in Australia to improve its ranking in sustainable development. Among all sectors, most of the UN SDGs are closely linked with the N cycle, demonstrating the crucial importance of sustainable N management in Australia.

3.1 Too-little nitrogen issues

The global mineral N fertilizer use has accelerated substantially, from ~11.4 Tg·yr^{-1} N in 1961 to 108 Tg·yr^{-1} N in 2019[11]. The growth in mineral N fertilizer use in Australia was slow compared with the rest of the world before the mid-1990s (Fig. 1(a)) with little applied to dryland crops because the yield did not reliably respond to applied N at the time[13,14]. With an increased area of canola production, more efficient fertilizer spreaders and increased premiums for high grain protein, there was a boom in N fertilizer use after the mid-1990s and the upward course resumed after the millennium drought of 2002–2009[15], but Australian fertilizer use is still only 1% of world consumption (Fig. 1(a)). Based on yield potential and on area of arable land, Australia's fertilizer use is much less than the world average (Table 1). Non-fertilizer sources of N (i.e., BNF, atmospheric deposition and soil organic matter to mineralized N) provide a significant amount of N input for agricultural production and make Australian agricultural ecosystems less dependent on fertilizer N (Table 1). However, stocks of soil N are limited resources and current trends indicate that accumulated N deficits are steadily increasing in many cropping soils across Australia[17]. In dryland grain production systems in particular, e.g., wheat, the N inputs to soil (around 26 kg·ha^{-1}·yr^{-1} N in 2010) are insufficient to replenish the N removed in grain (40 kg·ha^{-1}·yr^{-1} N at a low yield of 2 t·ha^{-1}), which leads to the steady decline in soil N and organic carbon, as well as a lower yield compared to the world standards (Fig. 1(b)).

3.2 Too-much nitrogen issues

In contrast, over 0.6 Mt of N fertilizer are used annually in Australia's intensive agricultural production systems, including high-value fruit, nut, vegetable, sugar and cotton industries[12]. The fertilizer N use efficiency (NUE) is low in these systems with more than 50% (and up to 80%) of applied N lost to the environment by NH_3 volatilization, nitrification-denitrification losses (NO_x, N_2O and N_2), leaching and runoff[18]. Such unwanted Nr losses represent not only significant economic losses to primary producers but cause serious environmental problems, including damage to the natural regions such as the Great Barrier Reef[19].

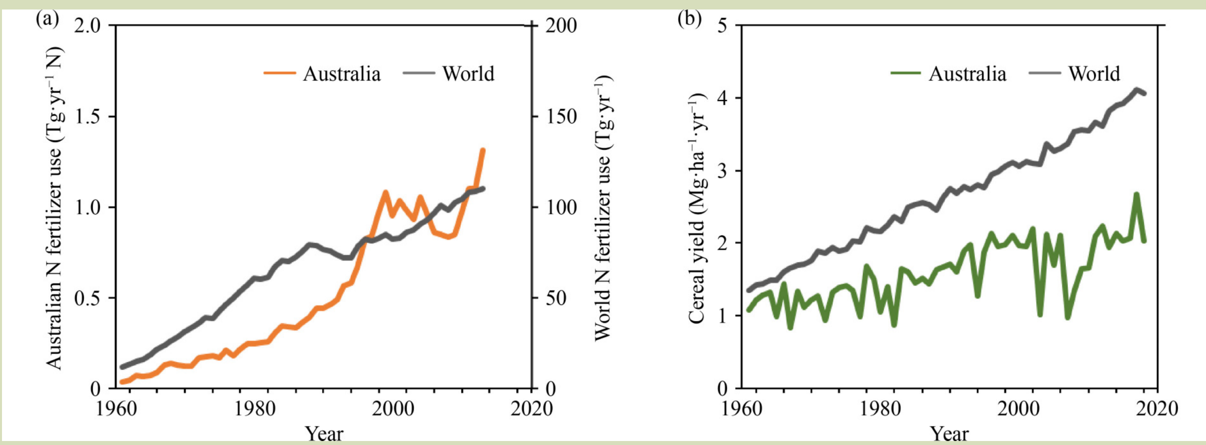


Fig. 1 Changes in N fertilizer use (a) and cereal yield (b) in Australia and the world. The sources are International Fertilizer Association[12] and Food and Agriculture Organization of the United Nations Statistical Databases[11].

Table 1 Estimated N inputs and outputs ($Tg\cdot yr^{-1}$) to agricultural production systems in Australia and the world in early 2010

Item	Australia[15]	World[16]
N inputs ($Tg\cdot yr^{-1}$)		
Inorganic fertilizers	1.5	116
Biological fixation	5.3	36
Atmospheric deposition	2.2	21
N outputs ($Tg\cdot yr^{-1}$)		
Plant-based food	1.2	20
Animal-based food	0.7	11
Area of arable land (Mha)	32	1378

Meanwhile, there is a too-much N issue for intensive feedlots in Australia. From intensive cattle feedlots in southern Australia as an example, NH_3 emissions are around 10.4–30.5 $Mg\cdot ha^{-1}\cdot yr^{-1}$ NH_3-N, which may result in environmental and health damage to the surrounding ecosystems and communities[20]. Australia-wide, N inputs on an average dairy farm increased from 91 $kg\cdot ha^{-1}$ N in 1990 to 214 $kg\cdot ha^{-1}$ N (production area basis) in 2012, while N outputs only increase from 36 to 57 $kg\cdot ha^{-1}$ N (production area basis), reflect the ongoing intensification of dairy production and increasing Nr losses from dairy farms of 54–158 $kg\cdot ha^{-1}$ N (production area basis) over this 22-year period[10].

Despite its clean green image, Australia has a large mean N footprint per person (47 $kg\cdot yr^{-1}$) both in food and energy sectors compared to the USA (39 $kg\cdot yr^{-1}$), Japan (28 $kg\cdot yr^{-1}$) and the EU countries (20–27 $kg\cdot yr^{-1}$) based on the N-calculator model[21–25]. Australia's style of food and energy production and consumption, especially for beef consumption and production and the heavy dependence on coal for electricity, explains its large food and energy N footprint.

More than half of the land is used for agricultural production in Australia, with more than 79% of agricultural products being exported to international markets[26]. Agricultural production provides food security and benefits the economy but has also exacerbated N management issues. The Australian National Farmers' Federation's 2030 Road Map sets an ambitious goal for agriculture to add value in excess of 100 Billion AUD by 2030 (63 Billion AUD in 2016–2017)[26]. Therefore, primary producers in Australia must try to reduce costs and increase productivity to maintain international competitiveness and increase profitability, which may aggravate both the too-little and too-much N issues and eventually undermine Australia's natural resources, environmental quality and food industries. One of the greatest challenges facing Australia is how to sustainably manage N to balance food security, environmental quality and economic development under climate change.

4 TECHNICAL AND SOCIOECONOMIC SOLUTIONS

To improve sustainable N management in Australia, it will be necessary to integrate agronomic, ecological and socioeconomic approaches and efforts (Fig. 2).

Technically, sustainable N use can be improved by advanced N management in crop production, e.g., 4Rs of N fertilizer application (selecting the right crop cultivar, planting at the right spacing and right time, using the right fertilizer and the right amount at the right time with the right placement). More effective synchrony of fertilizer N supply with crop demand can be achieved through improved fertilizer technologies, in particular enhanced efficiency N fertilizers (i.e., urease inhibitors, nitrification inhibitors, and controlled-release and slow-release fertilizers) and through improved management practices, including but not limited to split N applications, deep placement of fertilizer, conservation tillage, conservation buffers, soil amendment, irrigation management, erosion and sediment control. In animal production, improved N management can be achieved through feeding (e.g., low crude protein feeding, dietary supplements and phase feeding strategy), housing (e.g., air scrubbing techniques or bio filter, and rapid manure drying), storage and processing of manure (e.g., manure surface covers, acidic additives or cationic adsorbent, and aerobic composting), and application of manure (e.g., band spreading, incorporation and injection). Enhancing crop-livestock integration could improve N use efficiency by increasing fertilizer equivalence value of animal manure while mitigating excretal Nr losses, which could benefit to both the too-little and too-much N

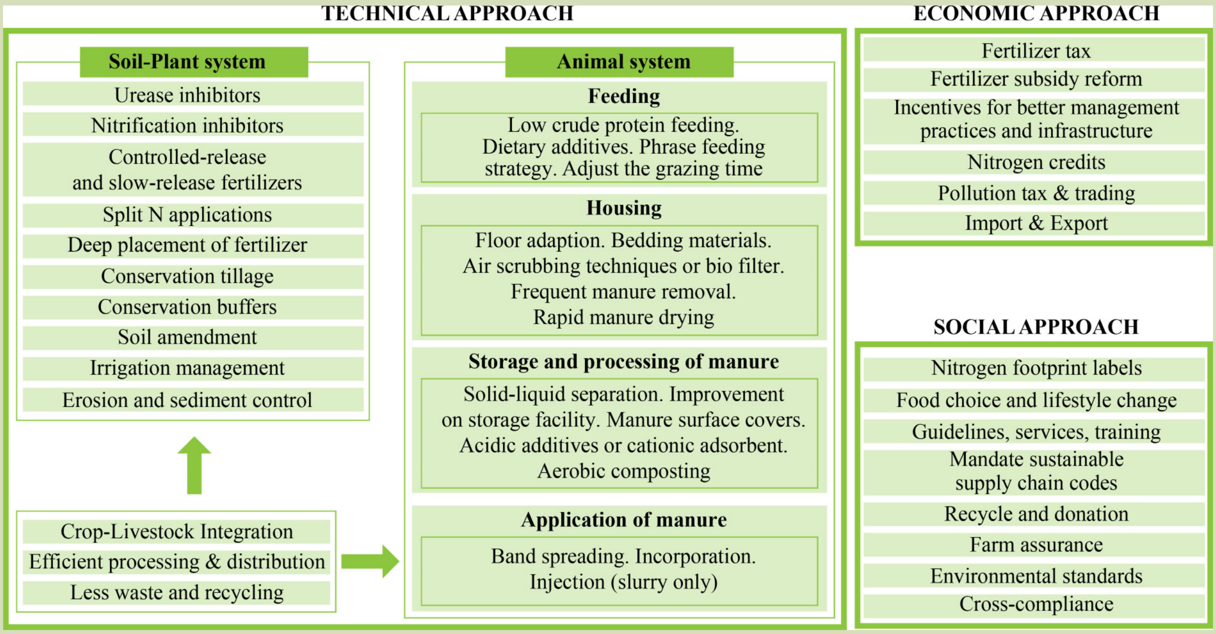


Fig. 2 Technical and socioeconomic solutions for sustainable nitrogen management in Australia.

issues in Australia[27].

Unlike point source pollution from industries and communities, N pollution from farms is diffuse as it results from large numbers of independently managed farms. The apparent discrepancy between the increasing availability of advanced technologies and increasing levels of N pollution indicates that the sustainability of N use cannot only rely on the effectiveness and availability of technologies and management practices. The economic, social and political interventions, such as regulatory standards, subsidies and tax, and market mechanisms need to be considered. For example, a framework of an N credit system is proposed to provide incentive-based mitigation strategies that acknowledges both the responsibilities and limitations of the multiple parties (suppliers, farmers, processors, retailers, consumers and regulators) across various agroecosystems for sustainable N management[28]. For example, the Australian Government has provided almost a billion AUD since 2013 in an attempt to rectify the deteriorating water quality of the Great Barrier Reef which could be used to support such a scheme to reduce N pollution from intensive farming[29]. For dryland wheat, N credits should be given for more sustainable measures to maintain the soil N reserves and reduce the risk of soil degradation and erosion. For pastures, vegetables and sugarcane production, N credits should be given to encourage reduced use of fertilizers and increased NUE. From the social aspect of sustainable N management, it needs individuals, collectives, institutions, cities and nations to reduce their Nr losses to the environment. This includes: (1) changing lifestyles to those with responsible consumption, such as choosing a diet with less meat, reducing food waste, taking public transportation and using more renewable energy; (2) promoting sustainable operations and policy planning; (3) facilitating interaction among producers, consumers, academic experts, administrators and other stakeholders to engage in dialogues that help to advance knowledge and responsibility sharing about sustainable N management.

5 FUTURE NEEDS AND OPPORTUNITIES FOR AUSTRALIA

Australian agricultural production and exports support food security and benefit the economy nationally and internationally. In 2017–2018, 66% of Australian total crop and livestock production was exported to overseas markets. China, Indonesia and Japan were the largest importers of Australian agricultural products, accounting for 27%, 14% and 10%, respectively. Countries importing agricultural commodities essentially purchase N resources from Australia, thereby saving N use and mitigating Nr losses they would otherwise have incurred. For example, more than 60% of Australia's total wheat production is exported each year mainly to Asia and the Middle East countries[30]. Producing 1 kg of wheat in Australia requires smaller N inputs than in China. Importing wheat from

Australia saves Nr use in China and elsewhere, but adds to the burden of soil N mining in Australia. Similarly, Japan imports around 80 $kt \cdot yr^{-1}$ of cheese in recent years from Australia[31], which relieves N pollution in Japan but adds to the burden of more N losses in Australia. At the global level, saving Nr use and mitigating Nr loss through trade occur if agricultural production in Australia has higher NUE than the importing countries, which may exacerbate both the too-little and too-much N issues in Australia. Given the increase in international trade, comprehensive information on the global N flows of food commodities between Australia and countries of consumption must be available to allocate responsibility for soil N mining or Nr losses of their imports from Australia by considering environmental cost, trade regulation, certification and product labeling.

The Seventh International N Conference held in Melbourne, Australia in 2016 published the “Melbourne Declaration on Responsible Nitrogen Management for a Sustainable Future” emphasizing the need to conduct regional and global N studies to address the triple challenges of food security, environmental degradation and climate change[32]. Around the globe, substantial efforts have been made to understand and contribute to sustainable N management from the field to local/regional scales, for example, the USA and EU have already completed their country-specific comprehensive assessments of N sources, fluxes and impacts[7]. However, the solutions for complex issues of sustainable N management must fit the conditions in the respective region and nation. To achieve sustainable N management globally in parallel, needs connected approaches and methodologies, benchmarking comparable indicators and indexes and spreading knowledge on effective N management among producers, consumers and policymakers[33]. It has been acknowledged that while N pollution is one of the most important environmental issues today, it needs to be incorporated within the broader concept of sustainability, like other elements (e.g., carbon, water and phosphorus), other sustainability issues (e.g., climate change, biodiversity loss and land use change) and other socioeconomic metrics of sustainability (e.g., food adequacy and safety, ecosystem stability, food affordability and availability, and sociocultural wellbeing).

6 CONCLUDING REMARKS

In the context of the rising demands for food and energy and the accelerating destruction of the environment, sustainably managing N to create and maintain the conditions under which humans and nature can exist in productive harmony to support the present and future generations is a major challenge. Since current N studies mainly focus more on agricultural and environmental targets and technical solutions, we argue that future studies should incorporate more socioeconomic perspectives for N sustainability to more meaningfully account for agricultural, environmental, societal and economic targets.

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Compliance with ethics guidelines

Xia Liang, Helen Suter, Shu Kee Lam, Charlie Walker, Roya Khalil, and Deli Chen declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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