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RIVIEW

A NEW APPROACH TO HOLISTIC NITROGEN MANAGEMENT IN CHINA

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KEYWORDS

4R technology, food chain N management, N use efficiency, soil-crop system, sustainable management

HIGHLIGHTS

- Progress on nitrogen management in agriculture is overviewed in China.
- 4R principles are key to high N use efficiency and low N losses in soil-crop systems.
- A new framework of food-chain-N-management is proposed.
- China’s success in N management provides models for other countries.

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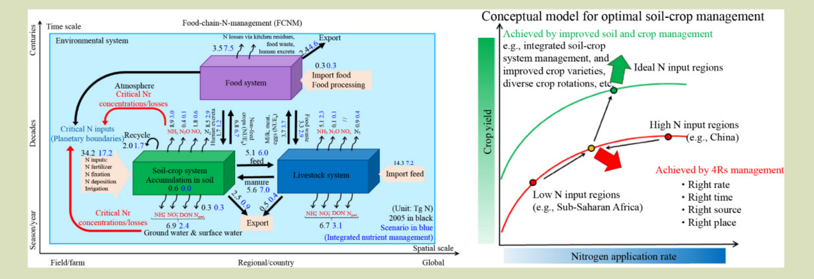
GRAPHICAL ABSTRACT



ABSTRACT

Since the 1980s, the widespread use of N fertilizer has not only resulted in a strong increase in agricultural productivity but also caused a number of environmental problems, induced by excess reactive N emissions. A range of approaches to improve N management for increased agricultural production together with reduced environmental impacts has been proposed. The 4R principles (right product, right amount, right time and right place) for N fertilizer application have been essential for improving crop productivity and N use efficiency while reducing N losses. For example, site-specific N management (as part of 4R practice) reduced N fertilizer use by 32% and increased yield by 5% in China. However, it has not been enough to overcome the challenge of producing more food with reduced impact on the environment and health. This paper proposes a new framework of food-chain-nitrogen-management (FCNM). This involves good N management including the recycling of organic manures, optimized crop and animal production and improved human diets, with the aim of maximizing resource use efficiency and minimizing environmental emissions. FCNM could meet future challenges for food demand, resource sustainability and environmental safety, key issues for green agricultural transformation in China and other countries.

1 INTRODUCTION

Due to the increasing population and demand for more livestock products, global cereal production has increased 2.9 times from 1961 to 2012[1] (3.4 fold by 2019), and this food/feed requirement is expected to further increase by at least 54% from 2012 to 2050[2]. Before the availability of nitrogen fertilizers synthesized by the Haber-Bosch process (the industrial synthesis of ammonia from dinitrogen and hydrogen), soil fertility in 25% to 50% of global cropland was maintained by legumes, cover crops and recycling manures[3]. Production of synthetic N fertilizer is a remarkable invention that has played a significant role in producing food for at least half of the increasing global population[4]. However, its application should be minimized by the effective use of legumes and the recycling of plant waste (compost), animal waste (manure) and human waste (sludge), with considerable benefits, for example, increases in soil organic carbon, soil biota and water-holding capacity[5,6]. Nitrogen fertilizer use increased almost 10-fold between 1961 and 2018[7], supporting the rapid increase in global cereal production resulting from the green revolution begun in the 1960s[8]. In China, N fertilizer consumption in agriculture has markedly increased from 0.5 Mt in 1961 to 28.3 Mt in 2018, peaking at 31.1 Mt in 2014[9]. Currently (2018 data), China accounts for around 26% of global consumption of agricultural N fertilizers.

However, the rapid increase in industrial fixed N together with its overuse or misuse (e.g., wrong time, form and method of application) with low NUE in about a third of the global cropland area[10] has caused a number of environmental pollution problems worldwide. The environmental problems are especially apparent in the major fertilizer consuming countries, for example, the OECD (Organization for Economic Cooperation and Development) member countries and the BRICS (abbreviations of five countries of Brazil, Russia, India, China and South Africa)[11]. On a global scale, the negative consequences of excess anthropogenic reactive N are increasing in time and space. Many, often interlinked, thresholds for human and ecosystem health have been exceeded, including those for drinking water quality (eutrophication driven by nitrates), air quality (smog, particulate matter, climate change and stratospheric ozone depletion) and biodiversity loss through acidification and eutrophication[12]. These environmental issues, in response to the rapid increase in anthropogenic N use, are a threat for several of the 17 Sustainable Development Goals (SDGs)[13] that have been adopted by the United Nations member states including threats to human health (SDG3), clean water (SDG6), ozone depletion and climate change (SDG13), the biodiversity and sustainably use of aquatic (marine) ecosystems (SDG14) and terrestrial ecosystems (SDG15). In China, ammonia emission from fertilized cropland causes secondary particulate pollution and enhanced N deposition[14]. Nitrate leaching and N runoff lead to nitrate pollution in groundwater and eutrophication in surface water (e.g., coastal seas, rivers and lakes)[15], and nitrous oxide emissions will accelerate global warming and also destroy the stratospheric ozone layer[16]. Excessive application of N fertilizer has further accelerated soil acidification[17], which will threaten cereal production in China if acidification continues[18]. Norse and Ju[19] reported the environmental costs of China's food security (largely due to overuse of N fertilizers) being up to 7% to 10% of China's agricultural gross domestic product or GDP. To avoid Nr related environmental problems, a safe operating space for the N planetary boundary was proposed in 2009[20] and revised in 2013 and 2015[21,22]. The key point of the N-safe planetary boundary concept is to increase N use efficiency (NUE) and decrease N loss to a safe level so that the Earth system can survive or at least tolerate the extra reactive N (Nr), although a new study by Hillebrand et al.[23] has challenged thresholds based on planetary boundaries.

This planetary N boundary, which focuses on the adverse impacts of N on air and water quality only, is however, affected by the NUE and does not account for the needed N in view of food security[21] while threats to SDG2 (zero hunger) should be avoided and N is arguably the most critical element for agriculture productivity, and consequently for food security[4]. More sustainable agricultural systems are needed that mitigate the negative effects of Nr and to promote improved NUE. This is critical for bringing N cycles back to the safe operating space, reconciling food security and environment targets, and thus achieving all relevant SDGs.

The efficiency of use of all N inputs to agriculture must be increased, combining maximal crop production with minimal emissions of Nr from farmland to natural and semi-natural environments, reducing ecological and environmental risks[15,24,25]. Optimized N management practices including the 4Rs (right source of N applied at the right rate, the right time and in the right place)[26] and ISSM (integrated soil-crop system management)[27] are increasingly important. For example, the Global Partnership on Nutrient Management and International Nitrogen Initiative have proposed the “20:20 for 2020” program, suggesting a 20% increase in NUE and 20 Mt reduction in fertilizer N input by 2020 relative to 2005[28]. However, policies in the past decades appeared inadequate to achieve this goal[29]. In 2015, China announced the zero increase program for fertilizer use by 2020 and achieved a reduction in N fertilizer use after 2016[30]. However, a recent detailed study from the USA showed the large spatial variability of NUE and crop yields due to variations in N inputs and cropping patterns[31]. Thus the challenges to reduce Nr emissions and so limit Nr pollution are growing[22,32,33]. Sustainable management of all N sources is urgently needed to maintain ecosystem functions and services[10,34] not only at field scale but also throughout the whole supply chain as described by Kanter and Searchinger[35]. In addition, the socioeconomic-environmental aspects of N management (e.g., linking food security, nutrition, health, resource use or recycling efficiency, environmental protection and sustainable development) need to be taken into account[36]. There is a close relationship between the planetary boundary and N management in China. The planetary boundary concept/approach provides overall N (or other nutrients) input threshold in order to realize the safe operation space whereas the N management approach points out how to makes it possible.

In this paper, we first present a historic overview of the environmental problems caused by inefficient N use in China. We then summarize current progress in N management for China’s green transformation of agriculture focusing on the farm and field scale (N inputs, their application technologies, soil-crop system management and trade-offs). Then we discuss future challenges and requirements of N management for food security and environmental sustainability, by improving the NUE and reducing N losses in the complete food chain and how these could be overcome using a food-chain-N-management (FCNM) approach in China. Finally, we discuss future needs for efficient N management.

2 REACTIVE N-INDUCED ENVIRONMENTAL PROBLEMS IN CHINA

Nitrogen is an essential element for life, but N inputs to ecosystems are often not fully utilized and the excess will remain in the soil or be lost to the environment. If the Nr in the ecosystem is beyond the environmental threshold, the emissions as gases and leaching or runoff will damage the local and wider environment until it is transformed back to N_2 (i.e., the N cascade[37]) (Fig. 1(a)). A good and increasing understanding of the biogeochemical cycle of N, the significant influences of human activities on the cycle and consequent environmental issues, already exists[38]. The N cascade concept provides a strong framework to identify the key intervention points and guide priorities, establish policy strategy, and develop technologies to overcome the adverse impacts of reactive N. Global problems of too much and too little Nr exist simultaneously, with some regions receiving too little N to sustain agriculture, resulting in insufficient food production and soil nutrient mining[38,39]. More attention has been paid to the *too-much* Nr induced environmental problems worldwide[14,40]. Unlike point source pollution from industries and human settlements, N pollution from agriculture is often diffuse or non-point source as it results from large numbers of independently managed farms, including both cropping and livestock production, making solving the problem more difficult[41]. Here we summarize five typical environmental problems induced by agricultural Nr emissions in China.

2.1 Air pollution

Air pollution is a widely recognized public health issue. At the national scale, agricultural NO_x emissions in China are limited compared to those generated by fuel combustion by industry, transportation and power plants[42]. However, China's agricultural NH_3 emissions were about 10 $Tg \cdot yr^{-1}$ N, contributing 80% to 90% of total NH_3 emissions in China[43]. Recent studies by Zhan et al.[44] and Liu et al.[45] further demonstrated that China was one of global hotspots of NH_3 emissions from agricultural activities including fertilized croplands. Once in the atmosphere, as an alkaline gas NH_3 readily combines with acid pollutants such as SO_2 and NO_x to form ammonium salts including NH_4NO_3 and $(NH_4)_2SO_4$[46]. These contribute to the formation of aerosols and particulate material (Fig. 1(b)). The most serious impact on human health is caused by $PM_{2.5}$ (particles less than 2.5 μm in aerodynamic diameter) that can deposit on pulmonary alveoli and damage lung function. $PM_{2.5}$ pollution is common in China, where Nr emission is believed to contribute 20% to 45% of the total[43,47]. Large reductions in $PM_{2.5}$ levels need to be achieved, especially by decreasing agricultural NH_3 and industrial and traffic NO_x emissions[42].

2.2 Greenhouse gas emissions

A disruption of the N cycle affects greenhouse gas (GHG) emissions in a complex way. N_2O emissions from agriculture[48], forests[49] and aquatic systems including coastal zones[50] have increased greatly since the preindustrial period, but net CO_2 uptake from the atmosphere has also increased through the stimulating effect of N deposition on the productivity of forest ecosystems[51]. Enhanced productivity may increase C sequestration in soil due to both increased litter production[52] and reduced decomposition of organic matter[53]. Total N_2O emissions in China increased from 224 Mt CO_2-eq in 1990 to 420 Mt CO_2-eq in 2013, and agricultural N_2O emissions accounted over 70% of this total, dominated by croplands (54% to 59%), followed by livestock (i.e., manure management, 18% to 27%) and biomass burning (1% to 2%)[54]. In addition, N fertilizer production and transport were important emission sources[55]. Using high resolution activity data and regional emission factors and parameters, Zhou et al.[56] reported much higher total N_2O emission (636 Mt CO_2-eq) in China in 2008, with comparable agricultural contribution (64%) to total national N_2O emission. Based on life cycle analysis, Kobayashi and Sago[57] calculated energy consumption and CO_2 emission in the manufacturing and transportation processes of N (and P) fertilizers. Follett[58] showed GHG emissions to be 45.5 kg CO_2 equivalent (CO_2-eq) kg^{-1} N produced and 3.0 kg CO_2-eq kg^{-1} N applied. According to Zhang et al.[59], the entire chain of N fertilizer production, transport and application contributed about 7% of national GHG emissions in China. In December 2020, the Chinese Central Government declared that the peak carbon or GHG emissions will appear by 2030 and Carbon Neutrality will be realized by 2060. Improved N management from fertilizer production, transport and application in agriculture can reduce about half of fertilizer induced GHGs emissions[59] and help to realize the carbon neutrality target for China.

2.3 Water pollution

It is well known that enrichment with Nr has adverse effects on water quality (Fig. 1(b). Next to phosphorus, N is a key nutrient causing eutrophication in fresh and coastal waters[60,61]. With the rapidly increasing global population, more and more Nr is released into waters causing serious damage[15,62]. To quantify the anthropogenic Nr impact on waters, a conceptual model NANI (net anthropogenic nitrogen inputs, including atmospheric N deposition, synthetic N fertilizer, biological N fixation and N in net food and feed imports) has been developed and applied in a number of watersheds in the USA, Europe and Asia[61,63,64]. The N flux out of a large watershed was a linear function of NANI, no matter what the source of the N (synthetic fertilizer, animal feed, atmospheric deposition), about 25% (ranging from 20% to 30%) flowed out to cause downstream pollution[62,65,66]. Gao et al.[67] reported that the riverine N flux in 15 catchments of the Lake Dianchi basin of south-west China was equal to 83% of the NANI on average, mainly due to the intensive agricultural activities and excessive N fertilizer use. A recent study[68] showed that agricultural fertilizer N input (743 $kg \cdot km^{-2} \cdot yr^{-1}$ N on average) contributed 64% to NANI globally, but with large spatial variations. River nutrient export, dominated by agriculture, was the largest source of pollution to the major Chinese seas (e.g., Yellow, Bohai and East China Seas)[69,70]. During 1970–2000, total dissolved N and P inputs to rivers increased two to 45 times (the range for subbasins), mainly due to changes in agriculture, with increased discharge of fertilizer N indirectly and manure directly to rivers[71]. Based on process-based models, Yu et al.[15] also reported the increased anthropogenic Nr losses to surface waters over the past five decades in China and Liu et al.[72] analyzed historic dynamics of Nr losses to Dianchi Lake under enhanced agricultural and industrial activities as well as urbanization.

2.4 Soil acidification

Soil acidification is a natural process that has been enhanced by anthropogenic activities, including overuse of N fertilizer[17]. Severe soil acidification was reported in major croplands[17], grasslands[73] and forest soils [74] in China. Industrial emissions of NO_x and SO_2, and increased N inputs to agriculture with elevated NH_3 emissions (that acidify soils when the NH_3 is

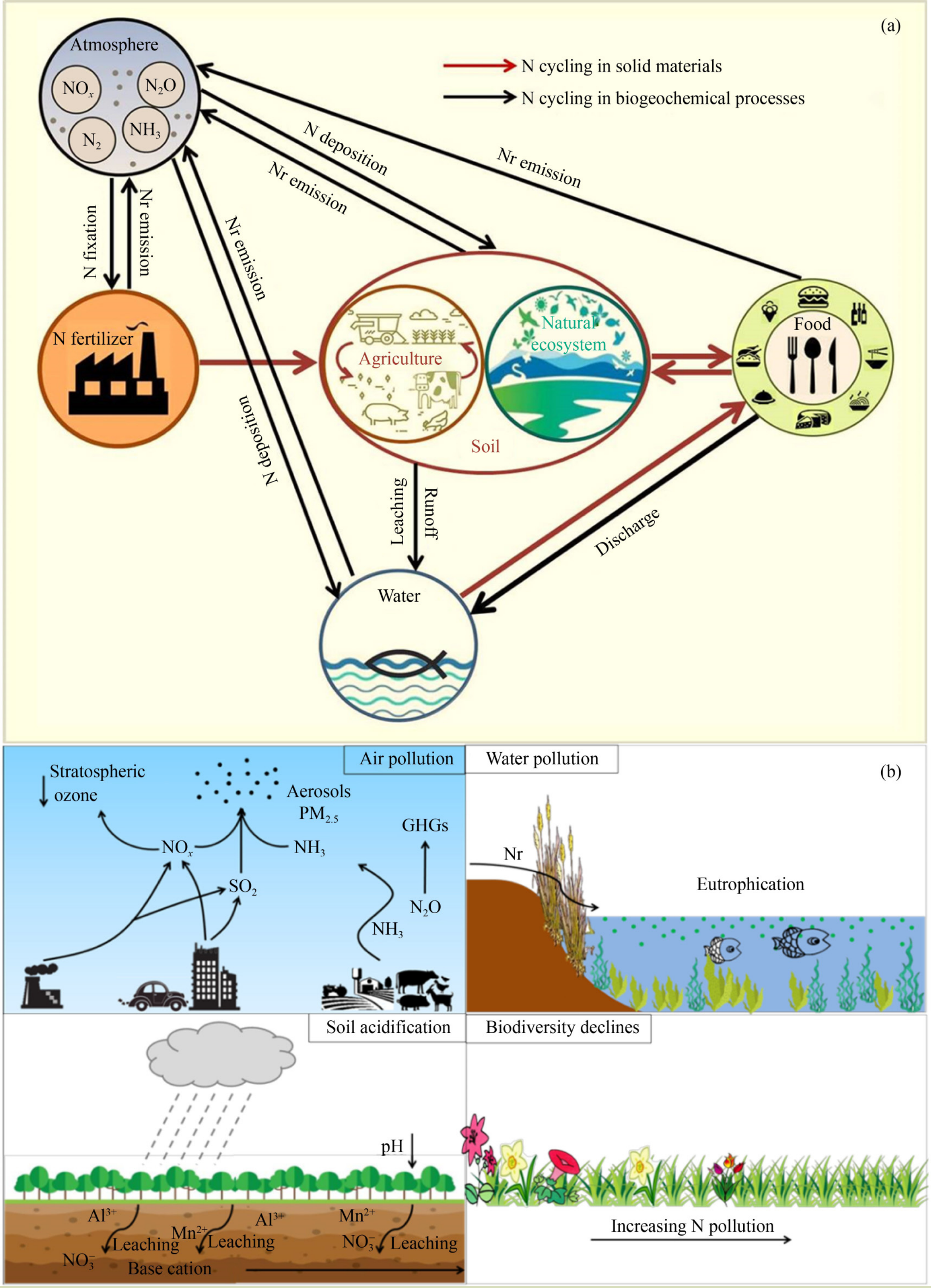


Fig. 1 Nitrogen cascade within agricultural and non-agricultural ecosystems (a) and the simplified impacts of reactive N (Nr) on air pollution and greenhouse gas emission, water pollution (including eutrophication), soil acidification, and biodiversity declines (b).

nitrified), have caused acid deposition and enhanced soil acidification, threatening ecosystem functioning and services in agricultural and non-agricultural systems[75–77]. Long-term N application has greatly increased crop yields[4,78] but increased the removal of base cations in harvested crops and the leaching of those cations with excess nitrate[79,80]. Soil acidification at pH levels below 4.5 leads to elevated concentrations of toxic elements such as aluminum and manganese (Fig. 1(b)), which can restrict plant and soil biota growth[81,82]. N-induced soil acidification decreased topsoil pH in Chinese croplands by 0.5 pH units on average between the 1980s and 2000s[17], and current N inputs may cause significant Al toxicity in the near future[83], declines in crop yields[18] and reduced bacterial diversity[84]. Balanced fertilization, combined with manure application can, however, reduce soil acidification and maintain crop yields[18].

2.5 Biodiversity decline caused by N deposition

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has published “Summary for policymakers of the global assessment report on biodiversity and ecosystem services (2019)”, which produced two important messages related to biodiversity loss: (1) about 25% of species are already threatened with extinction, and (2) the abundance of naturally present species has declined by 23% in terrestrial communities[85]. Despite national efforts to meet the Aichi Biodiversity Targets[86], anthropogenic drivers (including enhanced N deposition) of biodiversity loss are increasing globally[85,87].

The negative impacts of atmospheric N deposition on plant communities have been observed across many parts of the world[87,88]. Driven by the eutrophying and acidifying impacts of N on soils, effects range from direct toxicity at the highest levels of NH_3, such as those found close to a point source[89], to declines in sensitive higher plants[90–92] and lichens[93,94] as a result of chronic N deposition (also see Fig. 1(b)).

Bobbink et al.[87] have made a global assessment of the effects of N deposition on terrestrial plant diversity and reported biodiversity declines under elevated N deposition. The environmental problems induced by large amounts of deposited heavy N deposition and acid rain in European Union in the 1980s have led to a series of environmental laws and directives such as the 1996 Air Quality Framework Directive, an important legal milestone in the EU fight against air pollution, which set out a framework and basic principles for ambient air quality monitoring and management[95].

Other impacts of N deposition on biodiversity have been less visible. Based on observations of natural systems and N addition experiments, reductions in plant species richness associated with high levels of N deposition have been observed across China[96], as well as Europe[97] and the USA[98], with less competitive species, especially forbs, reduced while grass species tend to increase[99]. The loss of forb species has the potential to be particularly damaging to pollinators[100] and there is growing evidence of negative impacts on invertebrates[101]. Although N deposition in China has experienced a complex trend of increasing, stabilizing and declining[14,102,103], the effects of N deposition on biodiversity demand attention.

3 PROGRESS ON N MANAGEMENT AT FARM AND FIELD SCALE IN CHINA

Nitrogen management is already a primary focus of agronomy, concerned with productivity, efficiency, the environment and the economics of modern farming. Increased international attention is now directed to improving the NUE as a result of improved N management from farm to the whole food chain[104,105]. Several factors account for low NUE and high Nr losses in intensively managed agroecosystems, including spatial and temporal mismatches between crop N demand and N supply from fertilizer, soil, atmospheric deposition and irrigation, a low capacity for N retention in agricultural soils, and challenges in predicting the dynamics of in-season crop N uptake and N mineralization[24,31]. In practice, large amounts of N applied to the crop at early growth stages when N uptake is low, directly increase ephemeral inorganic N pools, which are often not well-matched with crop N demand in space and time: the period of maximum N demand for annual crops is intense but short, often in the middle-late stage of crop growth, while fertilizers are often applied weeks before this maximum uptake period, making N vulnerable to loss to the environment.

China’s farmers traditionally applied nutrients mainly as organic manure and green manures (including legume crops), sustaining crop yields with little fertilizer input[106]. However, fertilizer has become the dominant N source in crop production in China since 1980[55]. Nitrogen management has experienced four major stages in China: (1) improved N fertilization; (2) use of N-efficient cultivars; (3) integrated soil-crop system management; (4) N management extended to livestock production and the food chain (crop and animal production and food processing). These are discussed below.

3.1 Improved mineral and organic N fertilization

In the 1980s and 1990s, due to fertilizer subsidies, lack of farmer knowledge, farmer risk-aversion and market shortcomings (too many products and little support)[107], N fertilizer was applied to cropland either in excess of the crop requirement, at the wrong time, or by surface application without irrigation (increasing NH_3 volatilization), resulting in high N surplus[108] and a particularly low NUE[25]. Since 2000, much research on improving NUE in crop production has emphasized the need for greater synchronization between crop N demand and N supply from all sources throughout the growing season[109,110]. 4R nutrient management, developed by the fertilizer industry and described by Johnston and Bruulsema[26] as the 'right source of nutrients, applied at the right rate, at the right time and in the right place', provides some basic guidelines for determining each R, contributing to food security and increase NUE, while improving environmental sustainability and economic returns (Fig. 2(a)). The FAO International Code of Conduct for the Sustainable Use and Management of Fertilizers states that "… site-specific nutrient management incorporating the 4Rs … is a requirement to close remaining yield gaps as well to reduce the environmental footprint of fertilizers". A meta-analysis in China by Xia et al.[111] reported that 4R practices significantly increased grain yields by 1.3% to 10%, reduced N_2O emissions by 5.4% to 40%, NH_3 emissions (except where nitrification inhibitors were applied) by 31% to 62%, N leaching by 14% to 37%, and N runoff by 16% to 45%. Cui et al.[112] reported the importance of 4R for N management focusing mainly on global Nr hotspots to reduce more N_2O emission and achieve environmental and food co-benefits. However, 4R principles are not always applicable, for example, if the cost of 4R practices is too high to get profits on smallholder farms.

In practice, most existing N fertilizer recommendations have followed 4R principles, although sometimes without one or more of the 4Rs[10,113]. For example, in-season N management (INM) integrates the right rate and timing with the crop growing season, and the use of all possible sources of N to provide a spatial and temporal match with crop demand and so reduce N losses in the field[114,115]. Using INM in regional field experiments on intensive wheat-maize rotations in China showed that N rates could be reduced from > 500 $kg \cdot ha^{-1} \cdot yr^{-1}$ N in farmer practice to 250–320 $kg \cdot ha^{-1} \cdot yr^{-1}$ N at the economically optimal N rate[114,116]. Similarly, site-specific N management in China reduced N fertilizer use by 32% and increased grain yield by 5% compared to farmer practice[117]. Recently, precision N management, in which the rate of fertilizer applied is adjusted within the field to the specific needs of the growing crop, has been proven to be a robust way of implementing 4R[118,119]. Adopting 4R principles also includes the use of the right N source (NH_4^+, NO_3^-, urea), such as enhanced efficiency fertilizers (controlled-release N fertilizer, nitrification inhibitors and urease inhibitors)[111,120]. Researchers have reported that N sources, especially enhanced efficiency fertilizers, increased yield and NUE[121,122]. However, 4R fertilizer practices focus only on external anthropogenic inputs, ignoring any mineralizable N in the soil, biological N fixation and applicable agroecological practices. With the effective use of soil N, biological fixation and manure[117], the development of biological and efficiency enhancing fertilizers[121–123] as part of 4R practice must be an increasingly important component of N management for sustainable agriculture. In addition, some N management practices (e.g., use of nitrification inhibitors) can significantly reduce one N

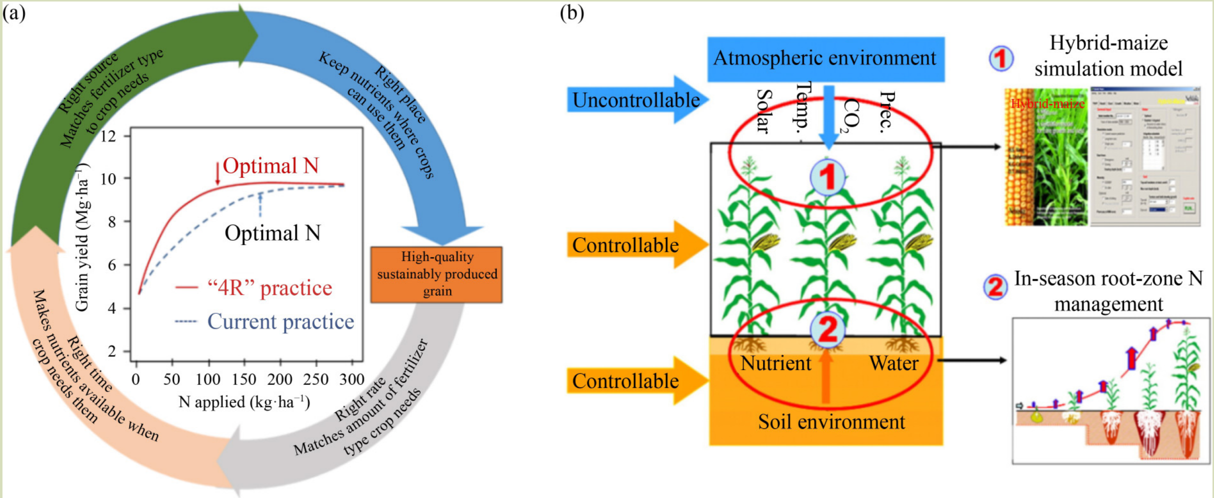


Fig. 2 Overview of optimized N management including the 4Rs (right rate, right source, right time and right place) for high-quality sustainably produced grain (a) and integrated soil-crop system management (b) (modified from Chen et al.[27]).

loss pathway (e.g., N_2O emission) but increase another N loss pathway (e.g., NH_3 emission), that is trade-offs, or pollution swapping[122,123]. A comprehensive assessment of the agronomic and environmental impacts of all N management practices in different environments and soils is needed, and INM and 4R practices and principles must be carefully designed to meet site-specific biophysical and human contexts and tested to provide scientific evidence for effectiveness.

Recycling of organic N in manure, straw and legume cover crops can partially substitute for fertilizer and improve soil quality[111]. Some aspects of the trade-offs when recycling organic N sources have been addressed in recent studies[111,124,125]. Experiments have given inconsistent results for crop yields, both positive[126] and negative[127], depending on environmental conditions such as soil properties, management practices, the organic source and substitution rates. Xia et al.[128] evaluated the responses of crop yield and gaseous emissions to partial substitution of fertilizer by manure, based on a global data set. Substituting fertilizer by livestock manure (at equivalent N rates applied with deep placement) increased crop yields by 4.4% and decreased Nr losses via NH_3 emissions by 27%, N leaching by 30% and N runoff by 26% in China. This effect is mainly due to the addition of base cations in manure, thus counteracting soil acidification and related crop yield loss, thereby increasing the NUE.

3.2 Use of N efficient crop cultivars

Besides improvement of N fertilizer application, it is important to develop crops that are able to efficiently utilize N sources in soils and produce high yield at optimal N inputs[129]. Development of N-efficient crop cultivars can be achieved by breeding. Indeed, compared to older cultivars (1985–1999), the newer cultivars of maize, wheat and rice developed in China (2000 and after) can produce more grain by 7.3% to 11%, improve N uptake by 5.2% to 8.5%, and reduce Nr emission by 9.6% to 24%, as revealed by meta-analysis[130]. A detailed evaluation of about 40 commercialized maize hybrids grown in north and north-east China indicated that N-efficient cultivars have the potential to improve yield by 8% to 10% and reduce the N fertilizer requirement by 16% to 21%[131]. Given the large numbers of smallholders in China, helping them to select advanced cultivars will produce more grain at lower environmental cost[107].

Breeding N-efficient cultivars is a considerable challenge because traits for N use efficiency are genetically complex and strongly interact with the environment. In general, the efficient cultivars have particular morphological and physiologic characteristics including (1) extensive root systems and high N uptake capacity for efficient N capture[132]; (2) enhanced photosynthesis, carbon and N metabolism and partitioning for efficient N utilization[133]; and (3) improved grain yield and quality[134]. The selection of crop cultivars in traditional breeding is mainly based on grain yield rather than NUE (although crop harvest index and NUE are tightly linked). For example, the Green Revolution greatly increased cereal yields through the adoption of semidwarf cultivars, but these require high N inputs to maximize yield[135]. In comparison the identification of novel gene alleles involved in gibberellin signaling in rice allows enhanced NUE without affecting yield[136,137]. The current advanced technologies such as genomic breeding and gene editing will accelerate to develop high-yielding and N-efficient cultivars for sustainable agriculture.

3.3 Integrated soil-crop system management

In addition to the 4R concept, an integrated soil-crop system management (ISSM) approach has been proposed and practiced in China[24,26], to increase resource use efficiency and productivity in intensive agricultural systems while reducing environmental damage. The idea of the ISSM design is to make maximum use of solar radiation and periods with favorable temperatures, to enable greater synchrony between crop demand for nutrients and their supply from the soil, environment and applied inputs (Fig. 2(b)). In current ISSM practices, two main steps are needed for a given region. First, a crop simulation model is used to identify the most appropriate combination of planting date, crop density and plant cultivar for a given site, based on the optimal use of solar and thermal resources. Second, a 4R nutrient supply model is used to provide a fertilizer recommendation, based on soil tests and the needs of the growing crop, to ensure non-limiting N supply with minimum losses to the environment[27]. Effective control of the total amount of N fertilizer, based on the target yield, combined with split N applications determined from a root-zone nitrate test were found to be key to in-season N management[110].

The ISSM practice has proved to be an innovative and environmentally friendly strategy in China. For example, the maize cv. Xianyu 335 (with relatively high planting density and short growing period) is more suitable for north-east China compared to cv. Zhengdan 958, another high-yielding cultivar with a longer growing period and moderate planting density[138]. ISSM-based recommendations at 153 experimental sites resulted in crop yield increases of 18% to 35% and improved N productivity (mass ratio of grain produced to N applied) of 32% to 46% compared to the common farmer practice[24]. Although promising, ISSM is location-specific and must be tailored to local circumstances; there is no one-size-fits-all solution to the complex problems of smallholder farmers in diverse agricultural systems. The required advances in ISSM in the future must come from a wide array of disciplines including basic and applied sciences that extend well beyond traditional agricultural sciences to embrace computer and computational science, including big-data analysis. However, to facilitate a wider adoption of ISSM worldwide, ISSM must be simplified to convince policymakers of the effectiveness of this technology[139].

Despite the effectiveness of ISSM in research projects, it is still a considerable challenge to transfer research results into farming practice in regions dominated by smallholder farming. Over the last decade the Chinese government has funded agricultural demonstration programs to support the transfer of knowledge and technology and soil testing programs to guide farmers in the efficient use of fertilizers throughout the country[140], resulting in greater yields and reduced environmental impact for millions of Chinese smallholders[139].

3.4 N management in livestock production

Historically, N management in China's traditional livestock production system referred only to manure collection, composting and application to croplands[141]. Since the 1980s, intensive livestock production has developed quickly, combined with the development of the animal feed industry (Li Defa, pers. comm.). Due to the limited cropland area, most intensive livestock farms in China are facing a major problem in how to recycle the excess manure. Therefore, N management on intensive livestock farms has been received increasing attention in China[142,143] as it has worldwide[144,145]. Currently N management in livestock production includes three components: (1) optimization of feed to increase animal N use efficiency, for example, supplying low protein feed; (2) improved management of animal housing, manure storage and composting; and (3) recycling of manure to croplands. For example, acidification of animal manure can lead to significantly reduced NH_3 and other nutrient losses during the composting process[146]. Recently, Zhang et al.[147] summarized various cost-effective manure management options to reduce NH_3 loss from dairy cattle production in China. Guo et al.[148] also reported annual agricultural NH_3 emission reductions of up to 34% using optimized agricultural cost-effective N management via the combined crop (fertilizer) and livestock (manure) system approach; as a consequence, air quality, NUE and food security in China were improved simultaneously.

3.5 Successful N management in China

Since the release of its fertilizer zero-increase action plan in 2015 and stricter environmental protection policies, China has successfully decreased its N fertilizer use by increasing adoption of the "Soil-Testing and Fertilizer Recommendation" program, changing fertilization practices by recycling manure and straw to replace at least some chemical fertilizer, mechanized application, fertigation and the development of new fertilizers, and through farmer demonstrations and government subsidies[30]. Using a global cropland-N_2O flux observation data set, nationwide survey-based reconstruction of N fertilization and irrigation, as well as an updated nonlinear model, Shang et al.[149] found weakened growth of cropland-N_2O emissions in China since 2003 which was associated with improved N management induced by nationwide policy interventions. In contrast to China, N fertilizer application in India continues to increase and its NUE to decrease[25,150], despite the introduction of neem-coated urea[151]. The achievements, challenges and solutions for enhancing agricultural sustainability differ across the world, from inputs that are inadequate to maintain soil fertility in many developing countries, particularly those of sub-Saharan Africa, to continued excessive and environmentally damaging surpluses in many developed and rapidly growing countries[40].

In China, the modern high-input, high-output system has provided the nation with basic food self-sufficiency, but at the cost of escalating environmental impacts (Fig. 3). However, the year 2003 represented an important turning point in fertilizer use efficiency when NUE of cereal crops reached a minimum (~25%), and efficiency was 15 percentage higher in 2018 than in 2003 (NUE_{total} as defined in Fig. 3). The combination of advances in crop breeding plus improved and integrated soil-crop system management has resulted in increasing on-farm yields while reducing environmental impacts[24]. From 2005 to 2015, about 20.9 million farmers in 452 counties in China adopted these enhanced management practices across a total of about 40 Mha[139]. As a consequence, average yields (maize, rice and wheat) increased by about 11%, N applications decreased by 15% to 18%, and estimated per unit yield Nr losses decreased by 27% to 30% (4.5–4.7 via 6.0–6.4 kg N t^{-1} yield). The effectiveness of improved practices has been increased through a truly novel approach to knowledge exchange: the Chinese Science and Technology Backyard program[107] in which research scientists, senior as well as junior, live in farming communities. By first practicing and

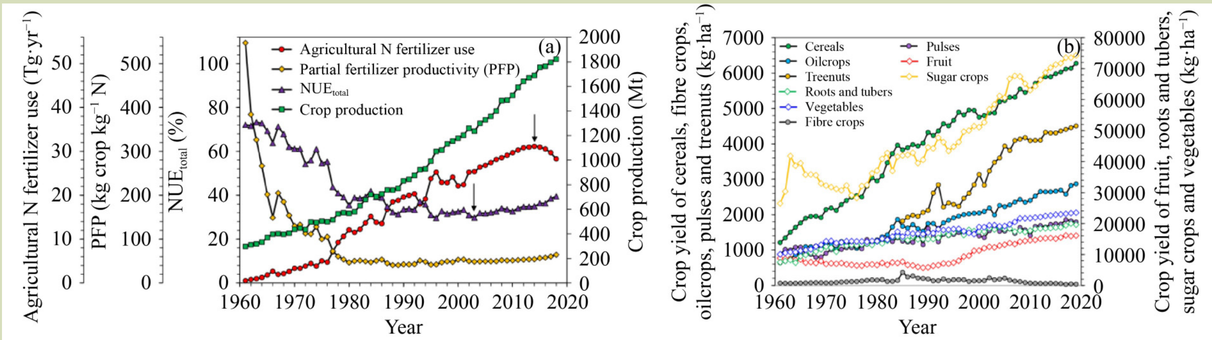


Fig. 3 Historical changes of synthetic N fertilizer use in agriculture, partial fertilizer productivity (PFP), total N use efficiency (NUE_{total}) and crop production in China during 1961–2018 (a); trends in yield for different crop categories in China during 1961–2018 (b). Data source: Food and Agricultural Organization of the United Nations. $NUE_{total} = N_{output}/N_{input} \times 100$, the ratio of N in harvested crops to the total N inputs, considering all N sources (i.e., N fertilizer, manure N, biological N fixation and deposition) in the soil-crop system.

then helping farmers test their novel agronomic approaches, this program has radically improved farm practice in China. National fertilizer use decreased from 60.2 Mt in 2015 to 56.5 Mt in 2019[152]. So far, this successful N management practice has been applied only to crop production systems, not animal production or the entire food chain. There is a long way to go to realize sustainable N management in coupled crop-animal systems and the food chain, as discussed below.

4 AN INTEGRATED FOOD-CHAIN-N-MANAGEMENT APPROACH FOR GREEN TRANSFORMATION OF AGRICULTURE IN CHINA

To feed the growing human population, research[153] has projected the global synthetic N demand to increase by 1.3% annually from 101 Tg N in 2010 to 132 Tg N in 2030, almost half of the increase related to cereal production. This will come at the cost of enhanced N losses to air and water unless the NUE is increased. Zhang et al.[25] projected the need for a global increase in NUE from 42% (2010) to 67% by 2050 to meet the increasing global food demand while reducing the N surplus to maintain acceptable air and water quality. Reconciling these projections will require the implementation of holistic agronomic approaches, including improved soil and N management across geographical regions (Table 1). In addition to improved system management, effective policies and campaign programs are needed to address the dual challenge of insufficient or excessive use of fertilizer N. There are reasons to be optimistic: excellent progress has been made in both technology and policy. National Governments in many countries have initiated strong campaigns and delivery programs to encourage the adoption of best N management practices[28,38] and the General Assembly of the UN Environment Programme has passed a resolution toward the development of a globally coherent approach of sustainable N management[154].

Sustainable agriculture or agriculture green development is a long-term strategy in China[155], essential for more effectively meeting the demand for food supply and affordability, and improved health and environments. Ma et al.[143] found that in the business as usual scenario, Chinese N fertilizer consumption in 2030 would increase by 25% throughout the whole food chain, driven by population growth and diet changes, while N losses would increase by 44% compared with that in 2005.

To address this challenge, more N-efficient technologies in food production alone are insufficient. It is crucial that food production and consumption are linked to the green transformation of agriculture in the context of healthy food and an acceptable living environment via nutrient flows across food chains, such as in the circular food system[156]. Apart from N losses during crop and animal production, there are N losses during food processing, transportation, storage and consumption[157]. Thus it is important to minimize N losses in the whole food production, supply and consumption system. Ma et al.[143] made an environmental assessment of management options for N flows through the whole food chain in China. Using the NUFFER model, Wang et al.[158] identified county-level N (and P) hotspots mostly distributed on the North China Plain and highlighted the importance of region-specific pollution control technologies for food production in China.

Table 1 Summarized N management strategies for global and selected geographic regions showing hotspots of total N inputs to cropland

Region	Total N input ($kg \cdot ha^{-1}$ N)	N management strategies	Global common
Africa	29 (10–60)	(1) Improved management of synthetic N ◇ 4R	(1) N acquisition and N utilization (2) Rhizospheric N_2 fixation
Australia	33 (20–80)	◇ SSNM	(3) N metabolism
South America	55 (30–80)	◇ LCC/SPAD	(4) Cereals fixing their own N
North America	91 (40–160)	◇ Inhibitors ◇ Controlled release sources	
Central Europe	113 (60–180)	(2) Improved management of other N sources	
South Asia	136 (60–300)	◇ FYM, crop residue, compost ◇ Biofertilizer and green manure	
East & South-east Asia	180 (80–400)	(3) System management ◇ Conservation agriculture ◇ Best management	

Note: 4R, right source, right rate, right time and right place; SSNM, site-specific nutrient management; LCC/SPAD, leaf color card with chlorophyll measurements; and FYM, farmyard manure. Data from Liu et al.[10].

Adapting these ideas, we propose an integrated framework for N management at various spatial and temporal scales (Fig. 4) that would meet food demands and environmental safety throughout the whole FCNM (food-chain-N-management) system. The framework includes the determination of critical N inputs to whole soil-crop-animal-food system (i.e., the entire food chain) and the balanced distribution of N resources between different regions and/or countries[11,42], considering both food production—consumption and environmental sustainability via estimated required human protein-N intake and environmental thresholds for specific Nr emissions[21]. Site-specific assessment of critical N inputs for, based on thresholds for different N compounds in air (NH_3), ground water (NO_3^-) and surface water (total) and the needed increase in NUE to reconcile food production with environmental quality has recently been made for Europe[159,160] and initiatives to apply these approaches at the county-level in China are currently underway.

The FCNM framework includes all major processes and stakeholders in the agrifood chain, which drive N pollution. Numerous studies[143,161,162] have quantified N budgets at specific spatial scales, from farm to county and/or region in China, but none has aligned N budgets across the whole food chain with essential needs and environmental impact, plus affordability. FCNM defines four components of the N management system: soil-crop, animal-crop, human-food and environment, connected by N consumption and leakage (Fig. 4).

(1) In Fig. 4(a), NUE_p, NUE_a, NUE_f denote N use efficiency in plant, animal and food systems, respectively; the scenario represents Integrated Nutrient Management (balanced fertilization, precision feeding and improved manure management are combined) and Dietary Change (a reduction in the increase in the consumption of animal-derived food while following Chinese food dietary guidelines); (2) In Fig. 4(b), the lower curve in red represents crop productivity from improved N management following 4R principles: (a) low N input regions, such as sub-Saharan Africa, where yield increases are limited by N availability as well as other potential factors (e.g., other nutrient deficiencies and water stress); (b) high N input regions, such as China, with a large N surplus in croplands due to high N inputs; (c) ideal N input regions showing crop productivity (the higher curve in green) based on improved soil and crop management such as Integrated soil-crop system management, and improved crop cultivars as well as diverse crop rotations.

To be effective the new framework should not only focus on the optimization of N but cover all aspects of the FCNM concept. It should include all processes throughout the whole food chain, including optimized diets, food consumption and food waste, and processes in which policy interventions could directly improve N management that benefit consumers (e.g., incentives for 4R technologies, household composting and straw return) and indirectly influence farm-level decision making (e.g., boosting education on food waste and low-N footprint dietary patterns and tax penalties and incentives for reducing the food N footprint)[163]. The key points of optimized N management in FCNM are to: (1) determine N inputs and balances in a specific area (a country, province, county or watershed, including soil, crop, animal and food); (2) calculate N fertilizer inputs based on crop demand and accounting for other N sources (including available organic manure); (3) use ISSM and the 4Rs to optimize crop management; (4) reduce N consumption with less food waste, but under the constraints of the N requirement of humans; and

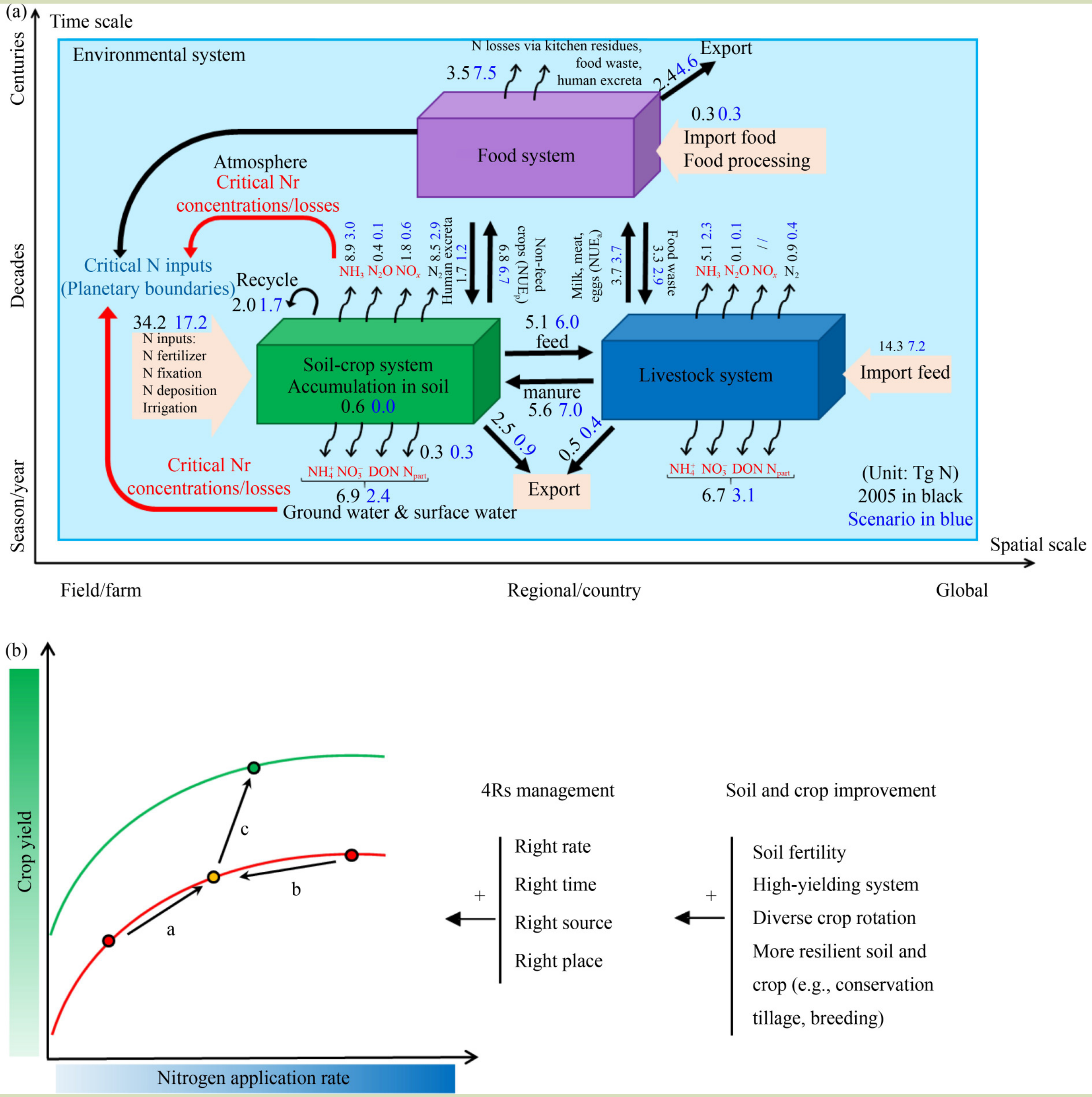


Fig. 4 An integrated framework for food-chain-N-management (FCNM) at regional and temporal scales, based on environmental thresholds (a) (data from Ma et al.[143]); and a conceptual model for optimal soil-crop management to achieve synchronous crop productivity, resource use efficiency and environmental protection (b).

(5) minimize N leakages along the food chain.

Based on previous efforts and the current understanding of N management[164], the important principles of the new framework must also include: (1) designing appropriate cropping and livestock systems for specific areas to meet food demand without damaging the environment[21,165]; (2) adopting site-specific N management using suitable fertilizer spreaders[166], enhanced efficiency fertilizers[122] and/or best manure management infrastructure[167]; and (3) reductions in food loss/waste through optimizing dietary habits, toward more balanced plant and animal diets.

In this context, a plant-based diet is not always effective in achieving sustainable food consumption. Human diets, containing protein from animals fed with low-cost feeds need less cropland than a vegetarian diet[168]. In terms of land use, the optimal amount of animals is related to the feed that comes from areas that cannot be used as crop land (e.g., extensive grazing areas) combined with use of food waste as animal feed. N management in feed crop production should consider both feed quantity and quality, that is, the nutritional requirement of animals, while manure management in animal production should consider the surrounding cropland area that can reuse organic manure, saving fertilizer and improving crop production. In addition, organic wastes in food processing and consumption should be reused or recycled within the FCNM system. Human nutrition needs to be guided toward a low-N footprint for food consumption through optimizing diets and reducing/recycling food waste, and focusing on benefits beyond food production[164], for example, biodiversity, landscape and education. To minimize the costs and maximize the benefits in food production, new agricultural technologies[166] and the improved managements of soil[27] water[32] and biodiversity[169] will be crucial, as well as improved N management via closing crop yield gaps and increasing resource efficiency while simultaneously decreasing environmental impacts. Creating good ecological and socioeconomic conditions[113], through appropriate regulations[170], are highly powerful pathways toward sustainable agriculture. Effective N management for agricultural green development also requires structural changes through education, transparent information and capacity building to improve social norms and values in favor of more sustainable consumption patterns and increase ability to practice sustainable food production and consumption patterns[171].

These changes span scales, affecting individual behavior, farms and farmers, the globalized food industry, urban development and spatial planning. For example, the crop production and animal production are relatively disconnected systems in current Chinese agriculture. In the FCNM system, however, the both sectors are connected closely and linked to the food system.

5 FUTURE DIRECTIONS AND RECOMMENDATIONS

Improving N management is important for sustainable agriculture/agriculture green development. It will be challenging and costly to make improvements in food production that reduce environmental impact, especially for those areas receiving too much N, where best N management practices (e.g., smart machines[166], enhanced efficiency fertilizers[122] and best manure management infrastructure[167]) are not used. Learning from successful experiences in China shows that integrated N management through, for example, the FCNM system, will be essential for achieving a sustainable food supply with minimal N losses to the environment[159]. Smallholders need access to effective and flexible technologies, combined with the capacity to select and adapt practices appropriate to their farms, crops, and seasonal conditions, rather than a standardized, inflexible package. Policy reform including, but not limited to, liberalizing the fertilizer market, must be pursued, such as liberalizing collateral requirements for fertilizer imports and reducing credit guarantees. Improved open-pollinated hybrids will increase yields[143] but improved management, especially of soil fertility, will bring larger gains[141]; combining them is the ideal.

Site-specific solutions rather than a one-size-fits-all approach are needed. Although many effective N management practices have been identified worldwide, a long-term field research network is needed to design, test and improve optimal site-specific measures that follow 4R principles. A range of context-dependent coupling models/mechanisms will be needed for the different scales of farms, villages or larger areas such as counties, watersheds or even countries, that take into account the specific local production and business contexts, while addressing the main drivers of yield limitation and trade-offs between benefits and costs. For example, livestock numbers could be controlled to match cropland manure requirements in a livestock-dominated area, while animal numbers could be carefully increased in cereal-dominated areas[172] to provide manure to replace fertilizer and thereby increase farm incomes.

However, many N management practices remain regional/local for historical reasons, requiring policy measures and improved strategies to overcome barriers to improved practices[173]. For example, the ineffective management of manure (e.g., uncovered storage, discharges to surface waters) is one of the main causes of N pollution through NH_3 emissions and water contamination, and there are few regulations in China in which livestock production is increasing rapidly[155]. Crop and animal production need to be recoupled at appropriate scales[151,164] for improved NUE and pollution mitigation. Organic production, based on the integration of crop and animal production, has been shown to promote sustainable farming, increase food production per unit area and increase NUE, reducing N losses through improved utilization of legume crops and byproducts, reduced N fertilizer applications to non-legume crops and enhanced nutrient recycling[174,175]. However, regulations on controlling NH_3 emissions and aquatic Nr losses from the livestock production should be practiced strictly to protect air and water quality[29,42].

Global food waste was 14% of food produced in 2016[176]. Although a nongovernmental organization in China launched the Clean Your Plate campaign in 2013 to raise consumer awareness about food waste, according to estimates, the amount of food waste produced in China in 2018 exceeded 100 Mt[177]. Food waste can be used as animal feed safely when heat-treated[171]. About 35% of food waste is recycled into pig feed in Japan. Hence, public education and training to enable consumers to reduce food waste and related N pollution (via landfill), healthy diets with less meat consumption, and effective communication and interaction between consumers and producers are all necessary[145]. Government policy interventions for sustainable agriculture can effectively improve N management and influence farm-level decision making, involving actors along the food chain, for example, the fertilizer industry, farmers, farm advisors, processors and traders, retailers and consumers. Policies could include a fertilizer tax, but novel fertilizer technologies and fertilizer services for free market system, education, training and demonstration are all needed, especially for the farmers of China[163].

Improving N management is a long-term objective in moving toward sustainable agriculture, requiring an effective national nutrient monitoring encompassing all environmental sectors, as is common in many developed countries. This would track progress resulting from the implementation of improved nutrient management practices and support modeling and forecasting future problems. Legislation is inevitable whenever commercial and environmental imperatives conflict.

Resolving the complex and interacting issues of climate change, biodiversity loss and air and water pollution while providing healthy nutrition for the increasing global population will not be easy. The currently suggested approaches, for example, Steffen et al.[22] and Houlton et al.[36], all involve significant socioeconomic (lifestyle) changes. We have addressed just one aspect of these global issues—the contribution of food production—but on that affects all of the above by linking N management in agriculture and the benefits along the food chain.

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Compliance with ethics guidelines

Xuejun Liu, Zhenling Cui, Tianxiang Hao, Lixing Yuan, Ying Zhang, Baojing Gu, Wen Xu, Hao Ying, Weifeng Zhang, Tingyu Li, Xiaoyuan Yan, Keith Goulding, David Kanter, Robert Howarth, Carly Stevens, Jagdish Ladha, Qianqian Li, Lei Liu, Wim de Vries, and Fusuo Zhang 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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