



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Liang, X;Lam, SK;Zhang, X;Oenema, O;Chen, D

Title:

Pursuing sustainable nitrogen management following the “5 Ps” principles: Production, People, Planet, Policy and Partnerships

Date:

2021-09-01

Citation:

Liang, X., Lam, S. K., Zhang, X., Oenema, O. & Chen, D. (2021). Pursuing sustainable nitrogen management following the “5 Ps” principles: Production, People, Planet, Policy and Partnerships. *Global Environmental Change*, 70, <https://doi.org/10.1016/j.gloenvcha.2021.102346>.

Persistent Link:

<https://hdl.handle.net/11343/288206>

1 **Pursuing sustainable nitrogen management following the “5 Ps” principles: Production,**
2 **People, Planet, Policy and Partnerships**

3 **Abstract**

4 Nitrogen (N) is an essential nutrient to support life, but if poorly managed, can adversely affect
5 the environment, ecosystems and human health. The global challenge of achieving food security
6 with minimal ecosystem degradation and human health impacts hinges on sustainable N
7 management, which goes beyond farm level and requires concerted efforts from a range of
8 stakeholders. While various metrics have been developed to inform N management, most of them
9 focus on one or two stakeholders only. Few efforts have tried to integrate N metrics to derive a
10 coherent set of actions for all stakeholders. Here we propose the “5 Ps” principles (Production,
11 People, Planet, Policy and Partnerships) that shape guidelines for sustainable N management with
12 multidimensional N metrics (i.e., *N use efficiency*, *virtual N factor*, *N footprint*, *N neutrality*,
13 *reactive N spatial intensity*, *N boundary*, *N price* and *N equity*). The “5 Ps” principles address the
14 environmental, social and economic dimensions of sustainability. These principles allow
15 multidimensional evaluation of N management, highlight specific areas for improvement, direct
16 future research, and support the design of effective policy and legislation. They facilitate collective
17 actions of producers, consumers, researchers and policy makers towards sustainable N
18 management regionally and globally.

19

20 **Keywords:** Reactive nitrogen; sustainable management; integrated perspectives;
21 multidimensional metrics.

22

23 1. The global nitrogen dilemma

24 The global population has quadrupled during the last 100 years. Currently, more than half of the
25 population is nourished by crops grown with synthetic nitrogen (N) fertilizers. N is an essential
26 element for all life on earth and thus for food production, but is often in short supply under natural
27 conditions. Since the invention of the Haber-Bosch process in the early twentieth century, humans
28 have substantially accelerated the total production of reactive N (Nr: all species of N except
29 dinitrogen N (N₂)) for food and industrial production, from ~ 15 Tera-grams (Tg = 10¹²g) N yr⁻¹
30 in 1860 to 210 Tg N yr⁻¹ in 2010 (Erisman et al., 2008). With the pressure of growing population
31 and increasing consumption of fossil fuels and meat-intensive diets, the global N cycle is expected
32 to be expanded at a record pace (Bodirsky et al., 2012; Galloway et al., 2008; Mueller et al., 2012).

33 Although Nr inputs are essential for agricultural and industrial production (Fowler et al., 2013), a
34 large proportion of the Nr inputs is lost to the environment and cascades through the atmosphere,
35 aquatic and terrestrial ecosystems with multiple effects (Erisman et al., 2013; Galloway et al.,
36 2003a, b). In the atmosphere, Nr gives rise to smog (e.g. frequent smog events with high
37 concentrations of PM_{2.5} in China, Sun and Xu 2016), stratospheric ozone depletion, and enhanced
38 greenhouse effect. In terrestrial ecosystems, Nr leads to soil acidification, forest dieback, and
39 biodiversity loss. In marine and freshwater ecosystems, Nr contributes to groundwater pollution,
40 acidification and eutrophication, which causes algal blooms and biodiversity loss (e.g. the Great
41 Lakes Basin and the Great Barrier Reef) (De'ath et al., 2012; Hartig et al., 2020; Kroon et al.,
42 2016). The high levels of Nr in water and air have been directly and indirectly connected with
43 human ailments, diseases and allergies which influence human health and welfare. The cost of Nr-
44 related damage in the European Union (EU) has been estimated at 75 to 485 billion euro per year,
45 with 35 to 230 billion euro related to agriculture (Van Grinsven et al., 2013).

46 With current Nr losses, the planetary N boundary, which sets a “safe operating space” for
47 humanity, is being exceeded by two-fold (Steffen et al., 2015). Meanwhile, adequate human
48 nutrition continues to be a global challenge with 688 million people undernourished and 2 billion
49 people living with moderately or severely insecure food supplies in 2019 (FAOSTAT, 2021).
50 Current food insecurity and malnutrition are largely related to inadequate access of poor people to
51 nutritious food, not to food shortages, while diets of affluent people become richer in animal-
52 source food, which is associated with relatively large Nr losses. There is also pressing demand for
53 more sustainable N management in response to the UN Sustainable Development Goals (SDGs)
54 (United Nations, 2020). While a range of metrics have been developed to inform N management,
55 most of them focus only on one or two particular stakeholders. There have been few attempts to
56 integrate the various metrics with a framework to derive a coherent set of actions for all
57 stakeholders. Here we propose the “5 Ps” principles (Production, People, Planet, Policy and
58 Partnerships) to shape guidelines for sustainable N management with multidimensional N metrics
59 (i.e., *N use efficiency*, *virtual N factor*, *N footprint*, *N neutrality*, *reactive N spatial intensity*, *N*
60 *boundary*, *N price* and *N equity*) (Figure 1).

61 Figure 1. The “5 Ps” principles (Production, People, Planet, Policy and Partnerships) that shape guidelines for sustainable N
 62 management for all stakeholders. A multidimensional set of N metrics is presented, with corresponding scales, indicators,
 63 purposes, approaches, major end users and proposed applications for each principle.
 64

	Production		People		Planet		Policy	
Scale								
Indicator	N use efficiency (NUE)	Virtual N factor (VNF)	N footprint	N neutrality	Reactive N spatial intensity (NrSI)	N boundary	N price	N equity
Purpose	Assess agricultural production practices, defined as the ratio of N removed in the agricultural products to N inputs	Quantify the performance of N use and Nr losses along food supply chains based on life-cycle assessment	Quantify the Nr losses to the environment as a result of an entity's resource consumption	Prompt an entity to achieve zero net Nr release to the environment through N-reduction and N offsets	Map the geographic locations and the intensity of Nr losses to identify hotspots of N pollution	Explore the lower and upper safe N boundaries based on specific environmental and socio-economic conditions	Estimate and monetise the agronomic, environmental, and social costs and benefits of N use and Nr losses	Allocate N resources and attribute fair share of the responsibilities for N use and Nr losses across regions and nations
Approach	$NUE = \frac{N_{prod_outputs}}{N_{inputs}}$ $VNF = \frac{N_{inputs} - N_{food}}{N_{food}}$		$N \text{ footprint} = \sum N_{energy} + \sum N_{food_consumption} + \sum VNF \times N_{food_consumption}$ $N \text{ neutrality} = \sum N \text{ footprint}_{reduction} + \sum N \text{ footprint}_{offset}$		$NrSI = \sum VNF \times N/A + \sum N \text{ footprint} \times P/S$ $N_{prod_outputs} \leq N \text{ boundary} \leq N_{critical \ losses}$		$N \text{ price} = \sum Cost - \sum Benefit$ $N \text{ equity} = f_{intergovernmental}(N \text{ price}, \text{consumers, farmers, trade})$	
	<p>$N_{prod_outputs}$: productive outputs N, including all harvested agricultural products; N_{inputs}: N inputs, including synthetic fertilizer, atmospheric deposition, biological fixation, and manure; N_{food}: N in food products.</p>		<p>$N_{food_consumption}$: N in food products that has been consumed; N_{energy}: Nr losses by fossil fuel combustion for housing, transportation, and provision of goods and services; $N \text{ footprint}_{reduction}$: avoid and/or reduce the release of Nr from the related activities; $N \text{ footprint}_{offset}$: purchasing N offsets that compensate the residual/unavoidable Nr losses.</p>		<p>N: N production for each kind of agricultural products; A: land use for each kind of agricultural products; P: national population; S: national settled area; $N_{critical \ losses}$: critical limits for the emissions of NH_3, NO_x, N_2O, and NO_x leaching and runoff to water bodies with respect to adverse environmental impacts.</p>		<p>$\sum Cost$: the costs of intended N use to produce the products or services, and the costs of damage to the environment, resources, human health, ecosystems, climate and society (societal cost); $\sum Benefit$: the improvement of agricultural production and ecosystem services; f: an intergovernmental mechanism with a consistent procedure to manage N price, guide consumers' choice, incentivize farmers' practices, and promote fair share of the responsibilities for N use and Nr losses through trade.</p>	
Major end users	Producers	Consumers	Individuals, companies, institutions and countries		Researchers & Policy makers		Producers & Consumers Researchers & Policy makers	
Proposed approach	N label		N calculator		N mapping		N credit system	
Partnerships	<p>Improve partnerships to elicit positive change by: 1. Integration of agro-eco-socioeconomic dimensions; 2. Experiences sharing; 3. Cross-country collaborations; 4. International trade; 5. Integration of N management strategies with the effective and efficient use of other scarce resources.</p>						<p>Indicator</p> <ul style="list-style-type: none"> Number of involved stakeholders Number of joint commitments 	

65 2. Production: nitrogen use efficiency (NUE) and virtual nitrogen factor (VNF)

66 As an essential nutrient for food production, N use efficiency (NUE) in crop production, defined
67 as the percentage of N input that is removed in harvested products, is one of the most effective and
68 prevalent indicators for assessing practices of plant-based food production and potential Nr losses
69 (Quan et al., 2021; Zhang et al., 2015, 2020). Synthetic N fertilizer use by agriculture increased
70 rapidly between 1961 and 2016, from 12 to 108 Tg N yr⁻¹, while the efficiency of its use decreased
71 in most countries, partly due to “the law of diminishing returns” (Lassaletta et al., 2014; Zhang et
72 al., 2021). Globally, NUE of crop production varies widely among geographic regions and crop
73 types. For example, the national average NUE of cropping systems range from 25% in China to
74 68% in the USA and Canada and 72 % in Sub-Saharan Africa (Zhang et al., 2015). Animal-sourced
75 food production has a lower NUE (10–50%) compared to plant-based food (30–60%), depending
76 on animal species, feed ration and management (Parodi et al., 2018). The NUE of the whole food
77 production-consumption chain is the integrated indicator of whole food systems (Erisman et al.,
78 2018; Ma et al., 2013), but standardization of procedures is needed before proper comparisons can
79 be made.

80 A very high NUE in crop production is not necessarily sustainable in the long-term. For example,
81 N inputs to soil have been insufficient to replenish the N removed in grain in Australian wheat
82 production systems. This leads to a steady and relentless decline in soil N (Peoples et al., 2017).
83 The same occurs in many Sub-Saharan countries. Continuous “soil N mining” not only leads to
84 soil degradation, including declines in soil organic matter, soil erosion and reduced drought and
85 climate resilience, but also negatively affects yield and quality of crop products and eventually
86 undermines farmers’ profits and food industries (Godfray and Garnett, 2014; Jat et al., 2020). In
87 contrast, excessive N fertilizer use is common in intensive cropping systems in densely populated
88 regions (e.g. China, India) with very low fertilizer NUE. In these systems, as much as 50 to 80%
89 of applied N may be lost to the environment via ammonia (NH₃) volatilization, nitrification-
90 denitrification, leaching and runoff. Such unwanted Nr losses represent not only a high economic
91 loss to primary producers, but also cause serious environmental problems. Both “too low” and “too
92 high” NUEs in agroecosystems are not sustainable, especially over long time periods (EU Nitrogen
93 Expert Panel, 2020).

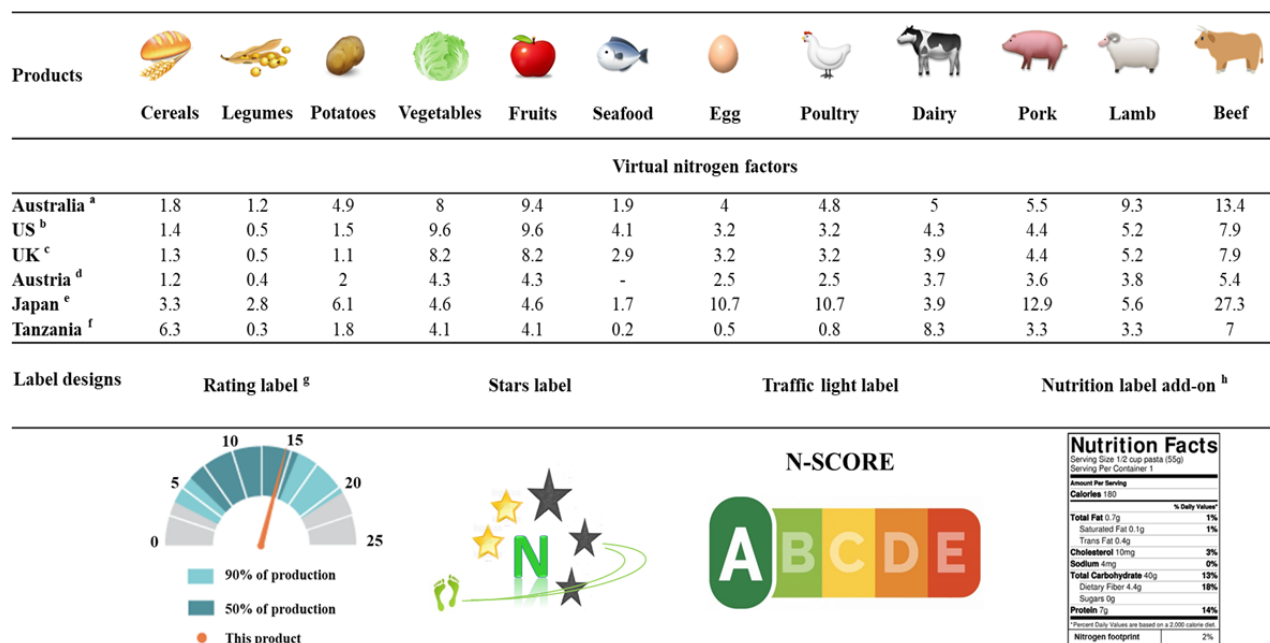
94 The virtual N factor (VNF) has been proposed as an indicator to quantify the performance of N
95 use and Nr losses along the whole food supply chain. This indicator is based on life-cycle
96 assessment and extends the system boundary from farms to marketplaces. So far, national VNFs
97 have been estimated for several countries (Figure 2). Cereals, legumes and seafood products
98 generally have lower VNFs compared to terrestrial animal products. The Nr losses per serving of
99 some vegetables and fruits are also relatively low due to their relatively low N content, although
100 they have relatively large VNFs. Beef from mature beef cattle is the least efficient in terms of N
101 use due to the large feed requirements, high basal metabolic rate and poor N management of animal
102 excretion (Hulbert et al., 2004) (Figure 2). The variation of VNFs of foodstuffs confirms the
103 importance of changes in human diets in reducing Nr losses due to food consumption. There are
104 large differences in VNFs between nations and agroecosystems. The VNF of a crop or animal
105 product in one country could be manyfold larger than its VNF in another country (e.g. VNF of egg
106 in Tanzania and Japan) (Figure 2). Within a country, the VNFs of food products can also differ
107 substantially due to differences in agroecosystems and practices. For example, more Nr per unit of
108 beef production is released to the environment from feedlot systems than from grazing systems in
109 Australia, since a much higher percentage (79%) of N excreted by grazing cattle returns to the

110 grassland compared to that from feedlot cattle (15%) (Liang et al., 2016). The comparisons
 111 between lamb produced from grazing versus feedlot systems, and seafood from wild-caught versus
 112 farmed systems also confirmed that lamb and seafood have lower VNFs when produced in
 113 extensive systems compared to intensive ones in Australia (Liang et al., 2016). These differences
 114 indicate large potential for reducing Nr losses associated with food production.

115 The VNFs of food products provide a means for consumers to compare Nr losses across and within
 116 product groups, which facilitates communication with wider audiences about impacts of dietary
 117 styles. A methodologically consistent procedure is needed to estimate VNFs of different food
 118 products from different producers accurately. The VNFs could be further explored for appealing
 119 and effective labels for food products, to be printed directly on a food product's packaging to help
 120 consumers make decisions at a grocery store. Four example labels (rating label, stars label, traffic
 121 light label and nutrition label add-on) are presented in Figure 2, to illustrate the case.

122

123 **Figure 2. Virtual nitrogen factors (VNFs; unit: kg Nr losses (kg consumed N)⁻¹) for major**
 124 **food categories as estimated for various countries. The lower half of the figure shows four**
 125 **example labels for communicating VNFs of food items to consumers.**



126

127 ^a Liang et al., 2016; ^b Leach et al., 2012; ^c Stevens et al., 2014; ^d Pierer et al., 2014; ^e Shibata et al.,
 128 2014; ^f Hutton et al., 2017; ^f developed from GLEAM <http://www.fao.org/gleam/en/>; ^h Leach et
 129 al., 2016.

130

131 3. People: nitrogen footprint and nitrogen neutrality

132 Environmental footprints have received increased popularity in sustainability research and
 133 ecological economics. The “footprint” concept has been developed over the last two decades to
 134 serve as a metric of single or collective impacts of human activities in terms of resource
 135 consumption and waste emission to the environment (Finnigan, 2004). The N footprint of a person
 136 or population has been developed as an indicator to quantify the Nr losses to the environment as a

137 result of an entity's resource consumption (Leach et al., 2012). It includes Nr losses from food
138 production, food consumption, fossil fuel combustion for housing and transportation, and
139 provision of goods and services. Using the N-Calculator model, the N footprint has been estimated
140 for several countries (i.e., Australia, United States of America, Netherlands, Germany, United
141 Kingdom, Japan, Austria) (Figure 3b). The N-Calculator is a consumer-based tool, which connects
142 individual consumption choices with Nr losses, and shows how lifestyle choices affect Nr losses.
143 Other approaches may be used to estimate N footprints. For example, Gu et al. (2013) used a mass
144 balance approach to estimate the N footprint for China. Further, a Multi-Region Input-Output
145 (MRIO) approach, which accounts for trade by tracking Nr losses through economic models, was
146 used to calculate the N footprint of 188 countries (Oita et al., 2016). However, these other
147 approaches focus less on consumers' behavior than the N-Calculator. The N footprint studies have
148 revealed the large contribution of lifestyle on Nr losses to the environment, while simultaneously
149 demonstrating the opportunities for lowering N footprints through changing lifestyle (e.g. choosing
150 a diet with less meat and using renewable energy) (Liang et al., 2016).

151 While Nr losses from food systems and fuel combustion can be decreased substantially, some Nr
152 losses are unavoidable. In response, the N-neutrality concept was proposed at the 6th International
153 Nitrogen Initiative (INI) 2013 Conference in Kampala, Uganda (Leip et al 2014). The idea is to
154 extend the concept of carbon neutrality (or net-zero carbon dioxide emissions) to N, and thereby
155 increase awareness about the consequences of Nr losses to the environment. The ultimate objective
156 of N-neutrality is to prompt an entity to achieve zero net Nr loss to the environment through (i)
157 taking measures that avoid and/or reduce the release of Nr from human activities (e.g. transport,
158 food consumption and energy use) (**N-reduction**), and (ii) purchasing N offsets that compensate
159 for the residual/unavoidable Nr losses (e.g. afforestation programs, food waste reduction projects)
160 (**N-offset**) (Leip et al 2014). The N-neutrality concept provides an opportunity for more sustainable
161 activities and events. It may be related to individual products, persons, companies, institutions and
162 countries, and requires a set of clear goals and monitoring to assess and improve their sustainability
163 (Galloway et al., 2014).

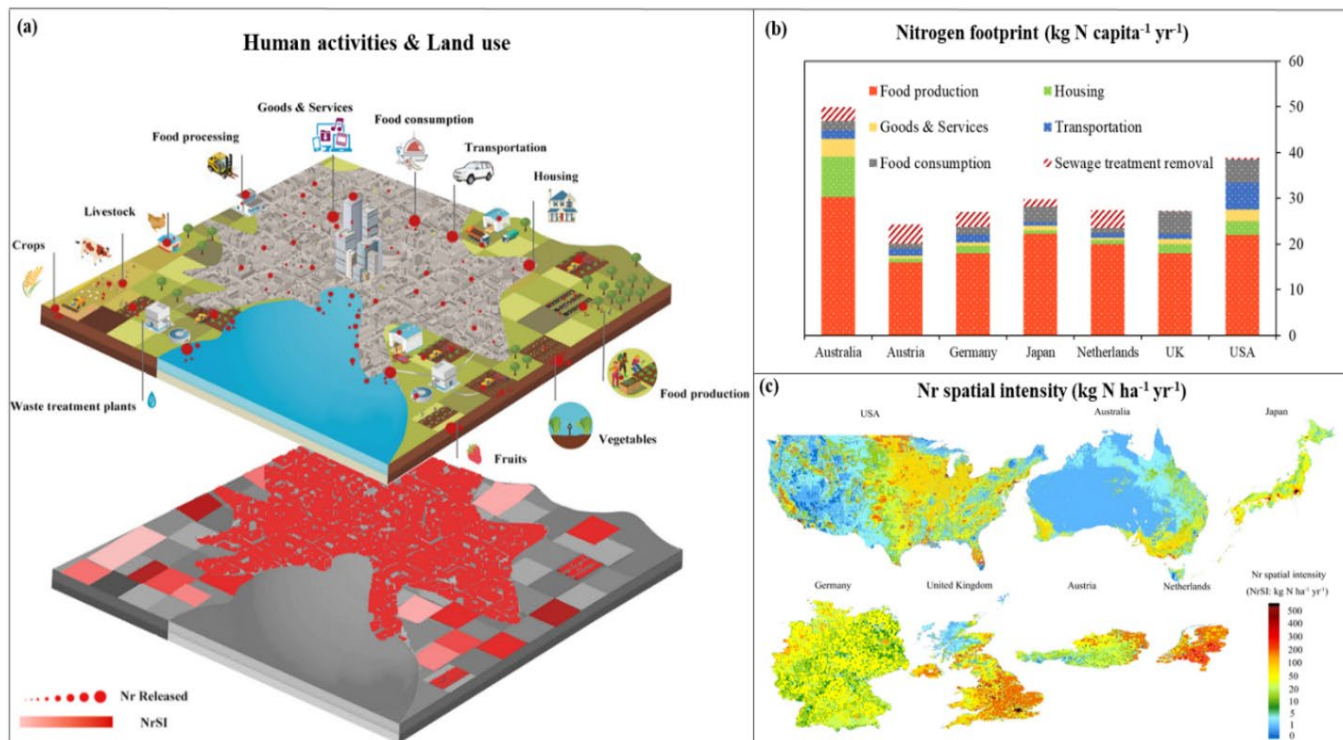
164 **4. Planet: spatial intensity of reactive nitrogen (NrSI) and nitrogen boundary**

165 The N footprint concept allows the public to understand the impact of their activities on Nr losses.
166 However, the N footprint is not directly connected to the resulting environmental impacts. The Nr
167 spatial intensity (NrSI) concept has been introduced to estimate the intensity of Nr losses on a per
168 area basis (Liang et al., 2018), and to map the intensity of Nr losses for geographic locations
169 (Figure 3a). The NrSI indicator and N footprint indicator may show large differences between
170 countries. For example, Australia had a large N footprint but low NrSI while the Netherlands had
171 a small N footprint but high NrSI (Figure 3b, c). The factors affecting the differences between N
172 footprint and NrSI include land area, population density, and volumes of imports and exports. The
173 environmental impacts of Nr losses depend on the Nr carrying capacity or the threshold of Nr
174 loading of an ecosystem (De Vries et al., 2013), and on the intensity of Nr losses. For intensive
175 feedlots, NH₃ emissions may range from 10 to 30 Mg NH₃-N ha⁻¹ yr⁻¹, and these emissions
176 damage the surrounding ecosystems and communities (Chen et al., 2015). For grazing systems,
177 the average NH₃ emission is often less than 1 kg NH₃-N ha⁻¹ yr⁻¹ and the majority is
178 redeposited locally, where it may contribute to pasture yield and soil carbon sequestration
179 instead of creating negative impacts (Smith et al., 2012). The NrSI indicator connects the total
180 Nr losses with the land area over which they are lost and can be used to indicate the potential for
181 environmental impacts, identify hotspots of Nr losses, and provide management recommendations

182 (Liang et al., 2018).

183

184 **Figure 3. Schematic diagram of the calculation of the Nr spatial intensity (NrSI; unit: kg Nr**
185 **loss ha⁻¹ yr⁻¹) for Melbourne (a), components and comparisons of national N footprints (kg**
186 **N capita⁻¹ yr⁻¹) (b) and spatial distribution of national NrSIs for selected countries (c). N**
187 **footprints quantify the per capita based Nr losses from food and energy production and**
188 **consumption and NrSI depicts the per area based Nr losses from food and energy production and**
189 **consumption to identify the hotspots of Nr losses by human activities (Sources: Carey et al., 2016**
190 **and Liang et al., 2016, 2018).**



191

192 To pursue sustainable N management it is necessary to sustain adequate and nutritious food
193 production in harmony with the environment, humans and nature. Earlier, it was proposed to use
194 “planetary boundaries for N” as a benchmark for the evaluation of the sustainability of N
195 management (De Vries et al., 2013; Willett et al., 2019). The planetary N boundary sets the
196 maximum N surplus, i.e. the difference between total N inputs and total N outputs in harvested
197 crop and animal products. Also, the NrSI for NH₃, NO_x, N₂O, NO₃⁻ leaching and runoff to water
198 bodies have to be below critical thresholds. With respect to food security, agricultural systems
199 generally need N inputs to meet N requirements of crops and animals. The “too little” N use may
200 lead to “soil N mining” and negatively affect soil health and crop production. The planetary N
201 boundary therefore should also guide minimum N inputs. For cropping systems, depending on the
202 current N management conditions, there are four main directions toward achieving sustainable N
203 management, including sustainable intensification, sustainable extensification, increasing N use
204 efficiency, and avoiding soil degradation (Figure 4). Technically, N management in crop
205 production can be improved through better fertilization, crop husbandry and soil cultivation
206 practices, e.g., planting at the right spacing and right time, using the right fertilizer with the right

207 amount at the right time and the right placement (4Rs of N fertilizer application). In animal
 208 production, N use efficiency can be improved through improved animal breeding, feeding and herd
 209 management practices, as well as through enhancing crop-livestock integration, so as to increase
 210 the fertilizer equivalence value of animal manure and to decrease excretal Nr losses (Sutton, et al.,
 211 2013).

212

213 **Figure 4. Framework for the evaluation of the N use efficiency in crop production, and**
 214 **directions (indicated by arrows) toward more sustainable N management.** Adapted and
 215 modified from EU Nitrogen Expert Panel (2020). The different numbers and colors indicate
 216 different situations, with 3 and the green color indicating adequacy, 1 and red too high NUE and
 217 5 and red too low NUE. The slope of the diagonal wedge represents a range of desired NUE
 218 between 50% and 90%: lower values exacerbate N pollution and higher values reflect mining of
 219 soil N stocks. The left vertical dotted white line indicates the desired minimum level of N inputs
 220 for the example cropping system (lower safe N boundary). The right vertical dotted white line
 221 represents a limit related to maximum N inputs (upper safe N boundary) to avoid substantial Nr
 222 losses. The numbers shown are illustrative of an example system and would vary according to
 223 context (e.g. crop species, climate and soil conditions).

224

225

226

227

228

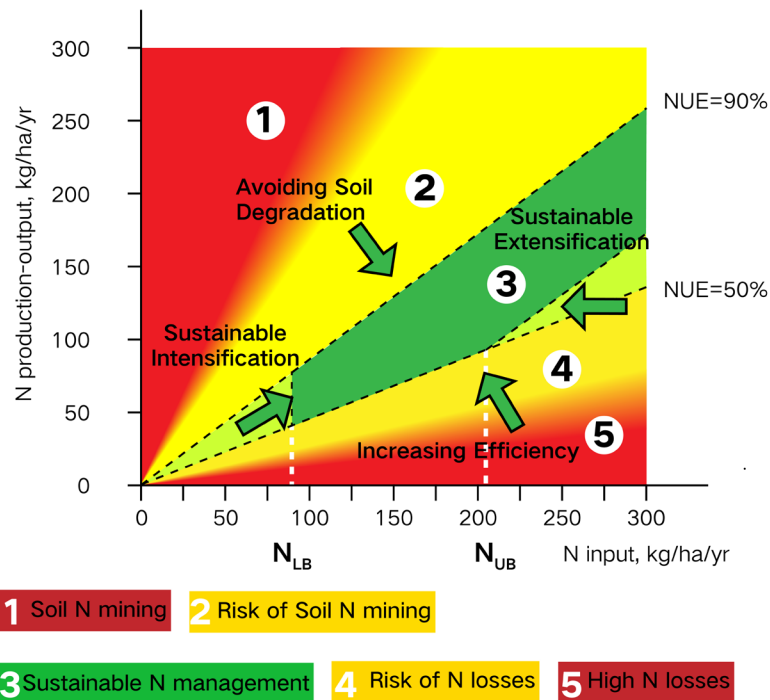
229

230

231

232

233



234 **5. Policy: nitrogen price and nitrogen equity**

235 For centuries, governments have provided incentives to farmers to improve food production
236 methods to increase and sustain the supply of safe and nutritious food and to protect the
237 environment. Governments facilitate agriculture through offering education programs, research
238 and development, and extension services. Some governments also support markets and provide
239 subsidies for the modernization of agricultural practices and for fertilizers and pesticides.
240 However, farmers in affluent countries (e.g. OECD countries) are also increasingly faced with
241 regulations and restrictions related to the use of fertilizers, pesticides and manure, as well as to
242 certain production methods (e.g. soil cultivation, animal housing). Global agri-food systems are
243 managed by a huge and diverse range of producers, in a wide range of soil and environmental
244 conditions, while using vastly different agronomic methods to produce numerous food products
245 (Poore and Nemecek, 2018). Human dietary patterns are also highly diverse, reflecting nutritional
246 requirements, access to markets, culture and personal preferences, and may change in response to
247 changes in biological, physiological and socioeconomic conditions (Fieldhouse, 2013).
248 Socioeconomic changes are necessary to provide adequate incentives for farmers to adopt certified
249 sustainable N management practices, and for consumers to choose certified sustainable N food
250 products.

251 The establishment of an N price based on cost-benefit analysis could provide the monetary value
252 of N use and Nr losses (Brink et al., 2011; Sobota et al., 2015; Van Grinsven et al., 2013), which
253 reflect both the costs of agricultural products for their N consumption and the costs of damage to
254 the environment, resources, human health, ecosystems, climate and society from Nr losses
255 (societal cost). The N price and a “bonus-penalty” system for price premiums or price levies could
256 have a range of formats and applications across stakeholders and for specific goals. For a farm, N
257 price could be used to award N premiums (N credits) to farmers who produce with lower N
258 pollution than their peers. For agricultural products, the N price could be used to append N levies
259 for products that are associated with high Nr losses per unit of nutrition (calorie or protein).

260 Among regions and agricultural systems, there is an uneven distribution of N resources and a huge
261 disparity in N management practices, ranging from “too much” N use in e.g. China and India to
262 “too little” N use in e.g. Sub-Saharan Africa (Zhang et al., 2017). Inequality in the use of N
263 resources is one of the defining issues of the global N dilemma and requires a commensurate focus
264 that, to date, has been lacking. Although it has been claimed that optimizing the allocation of N
265 resource among regions would maximize global NUE and mitigate Nr losses by 41% (Sutton, et
266 al., 2013), there are no intergovernmental mechanisms with targeted incentives for coordinated N
267 use at international level.

268 The increasing interconnectedness of global markets may aggravate the inequality in the use of N
269 resources. Countries importing agricultural commodities essentially purchase N resources, and
270 thereby reduce N use and Nr losses. Currently, importers of agricultural commodities do not pay
271 exporters for the externalities and associated societal cost of N use and Nr losses, particularly
272 where high-income countries obtain agricultural products from lower income countries at the cost
273 of those ecosystems and people (Stentiford et al., 2020). Many Sub-Saharan countries and West-
274 Asian countries import food as a means to achieve food security, because of low domestic food
275 production as a result of poor agricultural practices and/or water and land scarcity. Affluent
276 countries often import food and feed to sustain a luxurious diet of their consumers, without paying
277 for the externalities in exporting countries. Any policy aimed at charging importing countries the

278 the externalities and associated societal cost of N use and Nr losses of food production in exporting
279 countries must consider the different development stages of importers and exporters.

280 The establishment of an N price may provide great opportunity to achieve both N sustainability
281 and N equity globally, through guiding consumers' choice for agricultural products with lower Nr
282 losses, incentivizing farmers to adopt more sustainable N management practices, and promoting
283 the efficient allocation of N resource by fair share of the responsibilities for N use and Nr losses
284 through national and international trade. An intergovernmental mechanism with a
285 methodologically consistent procedure to create and manage N price and N equity is needed at
286 international level (Figure 1).

287 **6. Partnerships**

288 The N metrics for “Production”, “People”, “Planet”, and “Policy” principles provide guidance to
289 develop N management measures at multiple fronts along the food supply chain, and collectively
290 will lead to a research agenda and policy package aimed at facilitating “Partnerships” amongst
291 countries and amongst stakeholders (i.e. producers, suppliers and processing industries,
292 consumers, researchers, administrators and policy makers) (Figure 1). As these metrics were
293 designed with a range of focuses of various stakeholders, improvement in one N metric does not
294 necessarily lead to the improvement in all other N metrics, and sometimes even leads to
295 deterioration in some metrics (i.e., tradeoffs) (Figure 5). For example, a high NUE for farmers may
296 lead to “soil N mining” and degrade soil health, which negatively affects the safe N boundary. The
297 potential tradeoffs between N metrics, as well as their related stakeholders, may also exist between
298 regions or countries. For example, New Zealand exports around 3 million tonnes of dairy products
299 to more than 130 countries worldwide each year, which benefits the national economy and
300 improves global nutritional security (FAOSTAT, 2021), while its rapid growth in dairy farming
301 has substantially increased the concentrations of Nr in waterways, with nearly 67 percent of the
302 country's rivers carry pollution above acceptable levels (Ministry for the Environment & Stats NZ,
303 2020). Such tradeoffs, as well as possible synergies, revealed by the monitoring of N metrics,
304 demonstrate the necessity of partnership building across the boundaries of sectors and nations.
305 This will also help to identify common goals and shared responsibilities, and consequently guide
306 the coordination of efforts towards more sustainable N management.

307 The main activities of such a “Partnerships” include (i) sharing experiences among countries and
308 regions for better informed decision making; (ii) identifying priorities and targets in N
309 management and providing customized strategies across stakeholders and nations, while
310 considering inequities; (iii) collaborating on joint activities and monitoring of all metrics (Figure
311 1), and ensuring the necessary financial and knowledge support for such activities; (iv) promoting
312 the efficient allocation of N resources and fair share of the responsibilities and N costs of
313 production; (v) integrating N management strategies with the effective and efficient use of other
314 scarce resources (e.g. carbon, water, phosphorus, potassium and micronutrients), so as to better
315 achieve the UN SDGs.

316 For example, to tackle Australia's challenges of sustainable N management for both soil N mining
317 in rain-fed grain systems (“too little” N issue) and the excessive use of N in intensive crop and
318 animal production systems (“too much” N issue) (Hochman et al., 2013; Stott et al., 2016), the N
319 metrics for “Production”, “People”, “Planet”, and “Policy” principles in Australia will inform the
320 “Partnership” building among stakeholders and with Australian trade partners. Specifically, firstly,
321 the NUE and VNF of the “Production” principle will provide holistic assessments on N use and

322 Nr losses and benchmark N management performance across Australian agroecosystems (Figure
323 2, Liang et al., 2016); Secondly, the N footprint and N neutrality of the “People” principle will
324 provide national and sub-national assessments of anthropogenic Nr losses in Australia and
325 demonstrate the key drivers of Australia’s N footprint (e.g. beef and coal) (Figure 3, Liang et al.,
326 2016); Thirdly, the NrSI and N boundary of the “Planet” principle will identify the hotspots of
327 “too little” and “too much” N issues with a fine spatial resolution to prioritize the improvement of
328 N management across the country (Figure 3, Liang et al., 2018); Fourthly, Australia’s total crop
329 and livestock production contained 0.79 Tg N (equivalent to 4.9 Tg protein) in 2017-2018, with
330 66% exported to overseas markets. Countries importing agricultural commodities from Australia
331 reduce N use and Nr losses that they would otherwise have incurred, while aggravating both “too
332 little” and “too much” N issues in Australia. The N price and N equity of the “Policy” principle
333 will provide a socioeconomic perspective (e.g. societal cost, international trade) into Australian N
334 management studies to estimate and allocate fair share of an importing country’s responsibility for
335 the societal costs for the consumption of Australian agricultural products, which has not been done
336 before. Previous studies mainly focused on biophysical processes and management practices, but
337 with increasing international trade additional metrics will be needed. Lastly, the “Partnership”
338 principle will connect the other four principles and demonstrate how a collaborative and
339 multisectoral approach is needed to address Australia’s challenges of “too little” and “too much”
340 Nr and to achieve more sustainable N management.

341 **7. Future directions**

342 Improving N management requires proper indicators, tools, guidelines and incentives, as well as
343 targeted education, training and demonstrations. The N metrics at multidimensional levels form
344 the evidence to address both specific and general sustainability requirements. If put into practice,
345 each N metric with its proposed approach and application will serve as evidence and benchmarking
346 for the design, assessment and management of a particular system to address a specific
347 sustainability requirement (Figure 1). Collectively, the sequential N metrics will serve as evidence
348 and benchmarking for a top-down design, assessment and management of whole agroecosystems,
349 coupled with economic, social and environmental dimensions of sustainability (Figure 5). The
350 concept of the “5 Ps” requires policies and partnerships to make a clear understanding of the goals
351 and priorities for N management at a given scale. Governments, agricultural producers, other
352 industries, scientists and the public should engage to achieve optimal agricultural, environmental
353 and socio-economic outcomes for all dimensions and stakeholders.

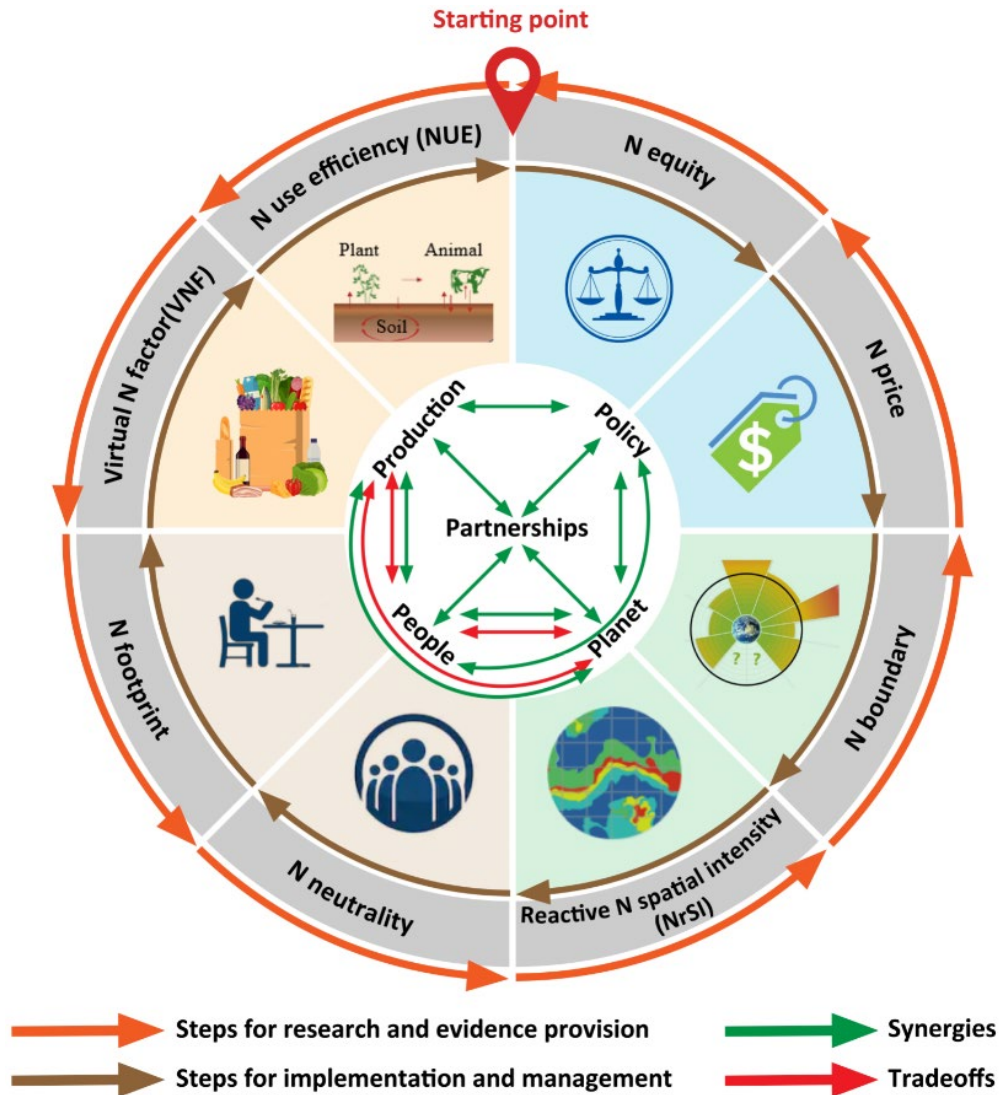
354 The “5 Ps” principles provide a unique framework to encapsulate a wide range of metrics that
355 cover most of the N management concerns along the food supply chain and enable the
356 identification of common spaces and priority areas for partnership building. Development and
357 application of the “5 Ps” principles include (i) improving the quantification of existing N metrics,
358 since many of the N metrics are based on budgeting approach, often with large uncertainties
359 (Zhang et al., 2015); (ii) improving the understanding of the interconnections among the N metrics,
360 especially the socioeconomic dynamics involved (e.g., market response) when translating the
361 performance of metrics of production to consumption, and/or upscaling the impacts of practice
362 changes from local to global scales (Metson et al., 2021; Zhang et al., 2015); (iii) exploring the
363 decision-making strategies with multiple goals and stakeholders involved in the “5 Ps” and using
364 “5 Ps” to enable and inform “intergovernmental mechanisms” of N use; (iv) strategizing the
365 communication of the metrics and “5 Ps” principles, and working with stakeholders to codevelop
366 case studies for the application of the “5 Ps”. While N management is of crucial importance for

367 sustainable food systems, there is also a clear need to examine the linkages between N management
 368 and greenhouse gas emissions, phosphorus cycling and water use etc. (Willett et al., 2019). The “5
 369 Ps” principles framework proposed here is flexible enough to provide these linkages.

370

371 **Figure 5. Interaction and integration of N metrics and “5 Ps” for evidence provision by**
 372 **bottom-up research** (anticlockwise, starting from 12 o’clock position, orange arrows) **and**
 373 **implementation by top-down management** (clockwise, starting from 12 o’clock position, brown

374 arrows). Synergies (green arrows) and tradeoffs (red arrows) exist across multiple principles.



375 **References**

- 376 Bodirsky, B.L., Popp, A., Weindl, I., Dietrich, J.P., Rolinski, S., Scheffele, L., Schmitz, C. and
377 Lotze-Campen, H., 2012. N₂O emissions from the global agricultural nitrogen cycle-current state
378 and future scenarios. *Biogeosciences*, 9(10), pp.4169-4197.
- 379 Brink, C., van Grinsven, H., Jacobsen, B.H. and Velthof, G.L., 2011. Costs and benefits of nitrogen
380 in the environment-Chapter 22. In *The European Nitrogen Assessment. Sources, effects and policy
381 perspectives* (pp. 513-540).
- 382 Chen, D., Sun, J., Bai, M., Dassanayake, K.B., Denmead, O.T. and Hill, J., 2015. A new cost-
383 effective method to mitigate ammonia loss from intensive cattle feedlots: application of lignite.
384 *Scientific reports*, 5(1), pp.1-5.
- 385 De Vries, W., Kros, J., Kroeze, C. and Seitzinger, S.P., 2013. Assessing planetary and regional
386 nitrogen boundaries related to food security and adverse environmental impacts. *Current Opinion
387 in Environmental Sustainability*, 5(3-4), pp.392-402.
- 388 De'ath, G., Fabricius, K.E., Sweatman, H. and Puotinen, M., 2012. The 27-year decline of coral
389 cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences*,
390 109(44), pp.17995-17999.
- 391 Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. and Winiwarter, W., 2008. How a century
392 of ammonia synthesis changed the world. *Nature Geoscience*, 1(10), pp.636-639.
- 393 Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B., Petrescu, A.R., Leach, A.M.
394 and de Vries, W., 2013. Consequences of human modification of the global nitrogen cycle.
395 *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621), p.20130116.
- 396 Erisman, J.W., Leach, A., Bleeker, A., Atwell, B., Cattaneo, L. and Galloway, J., 2018. An
397 integrated approach to a nitrogen use efficiency (NUE) indicator for the food production-
398 consumption chain. *Sustainability*, 10(4), p.925.
- 399 EU Nitrogen Expert Panel. Nitrogen Use Efficiency (NUE) - an indicator for the utilization of
400 nitrogen in agriculture and food systems. Wageningen University, Netherlands;
401 <http://www.eunep.com/wp-content/uploads/2017/03/N-ExpertPanel-NUE-Session-1.pdf>
402 (accessed March 15, 2020).
- 403 Food and Agricultural Organization of the United Nations Statistical Database (FAOSTAT), Food
404 Security sheet, Suite of Food Security Indicators, retrieved April 2021 from www.fao.org/faostat.
- 405 Food and Agricultural Organization of the United Nations Statistical Database (FAOSTAT), Trade
406 sheet, Crops and livestock products, retrieved May 2021 from www.fao.org/faostat.
- 407 Fieldhouse, P., 2013. *Food and nutrition: customs and culture*. Springer.
- 408 Finnigan, J., 2004. The footprint concept in complex terrain. *Agricultural and Forest Meteorology*,
409 127(3-4), pp.117-129.
- 410 Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A.,
411 Grizzetti, B., Galloway, J.N. and Vitousek, P., 2013. The global nitrogen cycle in the twenty-first
412 century. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621),
413 p.20130164.
- 414 Galloway, J.N., 2003a. The global nitrogen cycle. *Treatise on geochemistry*, 8, p.682.

415 Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. and
416 Cosby, B.J., 2003b. The nitrogen cascade. *Bioscience*, 53(4), pp.341-356.

417 Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli,
418 L.A., Seitzinger, S.P. and Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends,
419 questions, and potential solutions. *Science*, 320(5878), pp.889-892.

420 Galloway, J.N., Winiwarter, W., Leip, A., Leach, A.M., Bleeker, A. and Erisman, J.W., 2014.
421 Nitrogen footprints: past, present and future. *Environmental Research Letters*, 9(11), p.115003.

422 Global Livestock Environmental Assessment Model (GLEAM); <http://www.fao.org/gleam/en>
423 (accessed April 20, 2020).

424 Godfray, H.C.J. and Garnett, T., 2014. Food security and sustainable intensification. *Philosophical*
425 *transactions of the Royal Society B: biological sciences*, 369(1639), p.20120273.

426 Gu, B., Leach, A.M., Ma, L., Galloway, J.N., Chang, S.X., Ge, Y. and Chang, J., 2013. Nitrogen
427 footprint in China: food, energy, and nonfood goods. *Environmental science & technology*, 47(16),
428 pp.9217-9224.

429 Hartig, J.H., Krantzberg, G. and Alsip, P., 2020. Thirty-five years of restoring Great Lakes Areas
430 of Concern: Gradual progress, hopeful future. *Journal of Great Lakes Research*.

431 Hochman, Z., Carberry, P.S., Robertson, M.J., Gaydon, D.S., Bell, L.W. and McIntosh, P.C., 2013.
432 Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy*,
433 44, pp.109-123.

434 Hulbert, A.J. and Else, P.L., 2004. Basal metabolic rate: history, composition, regulation, and
435 usefulness. *Physiological and Biochemical Zoology*, 77(6), pp.869-876.

436 Hutton, M.O., Leach, A.M., Leip, A., Galloway, J.N., Bekunda, M., Sullivan, C. and Lesschen,
437 J.P., 2017. Toward a nitrogen footprint calculator for Tanzania. *Environmental Research Letters*,
438 12(3), p.034016.

439 Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A. and Gerard, B.,
440 2020. Conservation agriculture for sustainable intensification in South Asia. *Nature Sustainability*,
441 3(4), pp.336-343.

442 Kroon, F.J., Thorburn, P., Schaffelke, B. and Whitten, S., 2016. Towards protecting the Great
443 Barrier Reef from land-based pollution. *Global change biology*, 22(6), pp.1985-2002.

444 Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. and Garnier, J., 2014. 50 year trends in nitrogen
445 use efficiency of world cropping systems: the relationship between yield and nitrogen input to
446 cropland. *Environmental Research Letters*, 9(10), p.105011.

447 Leach, A.M., Emery, K.A., Gephart, J., Davis, K.F., Erisman, J.W., Leip, A., Pace, M.L.,
448 D'Odorico, P., Carr, J., Noll, L.C. and Castner, E., 2016. Environmental impact food labels
449 combining carbon, nitrogen, and water footprints. *Food Policy*, 61, pp.213-223.

450 Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R. and Kitzes, J., 2012. A nitrogen
451 footprint model to help consumers understand their role in nitrogen losses to the environment.
452 *Environmental Development*, 1(1), pp.40-66.

453 Leip, A., Leach, A., Musinguzi, P., Tumwesigye, T., Olupot, G., Tenywa, J.S., Mudiope, J.,
454 Hutton, O., d S Cordovil, C.M., Bekunda, M. and Galloway, J., 2014. Nitrogen-neutrality: a step

455 towards sustainability. *Environmental Research Letters*, 9(11), p.115001.

456 Liang, X., Leach, A.M., Galloway, J.N., Gu, B., Lam, S.K. and Chen, D., 2016. Beef and coal are
457 key drivers of Australia's high nitrogen footprint. *Scientific reports*, 6(1), pp.1-8.

458 Liang, X., Lam, S.K., Gu, B., Galloway, J.N., Leach, A.M. and Chen, D., 2018. Reactive nitrogen
459 spatial intensity (NrSI): a new indicator for environmental sustainability. *Global Environmental*
460 *Change*, 52, pp.101-107.

461 Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J. and Yang, H., 2010. A
462 high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National*
463 *Academy of Sciences*, 107(17), pp.8035-8040.

464 Ma, L., Wang, F., Zhang, W., Ma, W., Velthof, G., Qin, W., Oenema, O. and Zhang, F., 2013.
465 Environmental assessment of management options for nutrient flows in the food chain in China.
466 *Environmental science & technology*, 47(13), pp.7260-7268.

467 Metson, G.S., Chaudhary, A., Zhang, X., Houlton, B., Oita, A., Raghuram, N., Read, Q.D.,
468 Bouwman, L., Tian, H., Uwizeye, A. and Eagle, A.J., 2021. Nitrogen and the food system. *One*
469 *Earth*, 4(1), pp.3-7.

470 Ministry for the Environment & Stats NZ (2020). New Zealand's Environmental Reporting Series:
471 Our freshwater 2020. Available from www.mfe.govt.nz and www.stats.govt.nz.

472 Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N. and Foley, J.A., 2012.
473 Closing yield gaps through nutrient and water management. *Nature*, 490(7419), pp.254-257.

474 Muller, L., Lacroix, A. and Ruffieux, B., 2019. Environmental labelling and consumption changes:
475 A food choice experiment. *Environmental and resource economics*, 73(3), pp.871-897.

476 Oita, A., Malik, A., Kanemoto, K., Geschke, A., Nishijima, S. and Lenzen, M., 2016. Substantial
477 nitrogen pollution embedded in international trade. *Nature Geoscience*, 9(2), pp.111-115.

478 Parodi, A., Leip, A., De Boer, I.J.M., Slegers, P.M., Ziegler, F., Temme, E.H., Herrero, M.,
479 Tuomisto, H., Valin, H., Van Middelaar, C.E. and Van Loon, J.J.A., 2018. The potential of future
480 foods for sustainable and healthy diets. *Nature Sustainability*, 1(12), pp.782-789.

481 Peoples, M.B., Swan, A.D., Goward, L., Kirkegaard, J.A., Hunt, J.R., Li, G.D., Schwenke, G.D.,
482 Herridge, D.F., Moodie, M., Wilhelm, N. and Potter, T., 2017. Soil mineral nitrogen benefits
483 derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen
484 by wheat. *Soil Research*, 55(6), pp.600-615.

485 Pierer, M., Winiwarter, W., Leach, A.M. and Galloway, J.N., 2014. The nitrogen footprint of food
486 products and general consumption patterns in Austria. *Food Policy*, 49, pp.128-136.

487 Poore, J. and Nemecek, T., 2018. Reducing food's environmental impacts through producers and
488 consumers. *Science*, 360(6392), pp.987-992.

489 Quan, Z., Zhang, X., Fang, Y. and Davidson, E.A., 2021. Different quantification approaches for
490 nitrogen use efficiency lead to divergent estimates with varying advantages. *Nature Food*, 2(4),
491 pp.241-245.

492 Schmidt, H.J., 2009. Carbon footprinting, labelling and life cycle assessment. *The International*
493 *Journal of Life Cycle Assessment*, 14(1), pp.6-9.

494 Sharp, A. and Wheeler, M., 2013. Reducing householders' grocery carbon emissions: Carbon

495 literacy and carbon label preferences. *Australasian Marketing Journal (AMJ)*, 21(4), pp.240-249.

496 Shibata, H., Cattaneo, L.R., Leach, A.M. and Galloway, J.N., 2014. First approach to the Japanese
497 nitrogen footprint model to predict the loss of nitrogen to the environment. *Environmental*
498 *Research Letters*, 9(11), p.115013.

499 Smith, J.G., Eldridge, D.J. and Throop, H.L., 2012. Landform and vegetation patch type moderate
500 the effects of grazing-induced disturbance on carbon and nitrogen pools in a semi-arid woodland.
501 *Plant and Soil*, 360(1), pp.405-419.

502 Sobota, D.J., Compton, J.E., McCrackin, M.L. and Singh, S., 2015. Cost of reactive nitrogen
503 release from human activities to the environment in the United States. *Environmental Research*
504 *Letters*, 10(2), p.025006.

505 Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R.,
506 Carpenter, S.R., De Vries, W., De Wit, C.A. and Folke, C., 2015. Planetary boundaries: Guiding
507 human development on a changing planet. *Science*, 347(6223).

508 Stentiford, G.D., Bateman, I.J., Hinchliffe, S.J., Bass, D., Hartnell, R., Santos, E.M., Devlin, M.J.,
509 Feist, S.W., Taylor, N.G.H., Verner-Jeffreys, D.W. and van Aerle, R., 2020. Sustainable
510 aquaculture through the One Health lens. *Nature Food*, 1(8), pp.468-474.

511 Stevens, C.J., Leach, A.M., Dale, S. and Galloway, J.N., 2014. Personal nitrogen footprint tool for
512 the United Kingdom. *Environmental Science: Processes & Impacts*, 16(7), pp.1563-1569.

513 Stott, K.J. and Gourley, C.J., 2016. Intensification, nitrogen use and recovery in grazing-based
514 dairy systems. *Agricultural Systems*, 144, pp.101-112.

515 Sun, C., Yuan, X. and Xu, M., 2016. The public perceptions and willingness to pay: from the
516 perspective of the smog crisis in China. *Journal of Cleaner Production*, 112, pp.1635-1644.

517 Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven,
518 H. and Grizzetti, B. eds., 2011. *The European nitrogen assessment: sources, effects and policy*
519 *perspectives*. Cambridge University Press.

520 Sutton, M.A., Bleeker, A., Howard, C.M., Erisman, J.W., Abrol, Y.P., Bekunda, M., Datta, A.,
521 Davidson, E., De Vries, W., Oenema, O. and Zhang, F.S., 2013. *Our nutrient world. The challenge*
522 *to produce more food & energy with less pollution*. Centre for Ecology & Hydrology.

523 United Nations (2020). *The Sustainable Development Goals Report 2020*;
524 <https://unstats.un.org/sdgs/report/2020/> (accessed February 1, 2021).

525 Van Grinsven, H.J., Holland, M., Jacobsen, B.H., Klimont, Z., Sutton, M.A. and Jaap Willems,
526 W., 2013. Costs and benefits of nitrogen for Europe and implications for mitigation.
527 *Environmental science & technology*, 47(8), pp.3571-3579.

528 Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T.,
529 Tilman, D., DeClerck, F., Wood, A. and Jonell, M., 2019. Food in the Anthropocene: the EAT-
530 Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170),
531 pp.447-492.

532 Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P. and Shen, Y., 2015.
533 *Managing nitrogen for sustainable development*. *Nature*, 528(7580), pp.51-59.

534 Zhang, X., 2017. A plan for efficient use of nitrogen fertilizers. *Nature*, 543(7645), pp.322-323.

535 Zhang, X., Mauzerall, D.L., Davidson, E.A., Kanter, D.R. and Cai, R., 2015. The economic and
536 environmental consequences of implementing nitrogen-efficient technologies and management
537 practices in agriculture. *Journal of environmental quality*, 44(2), pp.312-324.

538 Zhang, X., Davidson, E.A., Zou, T., Lassaletta, L., Quan, Z., Li, T. and Zhang, W., 2020.
539 Quantifying nutrient budgets for sustainable nutrient management. *Global Biogeochemical*
540 *Cycles*, 34(3).

541 Zhang, X., Zou, T., Lassaletta, L., Mueller, N., Lisk, M.D., Lu, C., Conant, R., Gerber, J., Tian,
542 H., Bruulsema, T., Zhang, W., Nishina, K., Bodirsky, B., Popp, A., Bouwman, L., Beusen, A.,
543 Leclere, D., Canadell, P., Jackson, R., Tubiello, F., Davidson, E.A., 2021. Quantification of global
544 and national nitrogen budgets for crop production, *Nature Food*.