Beef and coal are key drivers of Australia’s high nitrogen footprint

Xia Liang1, Allison M. Leach2, James N. Galloway3, Baojing Gu1,4, Shu Kee Lam3 & Deli Chen1

Anthropogenic release of reactive nitrogen (Nr; all species of N except N2) to the global nitrogen (N) cycle is substantial and it negatively affects human and ecosystem health. A novel metric, the N footprint, provides a consumer-based perspective for Nr use efficiency and connects lifestyle choices with Nr losses. Here we report the first full-scale assessment of the anthropogenic Nr loss by Australians. Despite its ‘clean and green’ image, Australia has the largest N footprint (47 kg N cap−1 yr−1) both in food and energy sectors among all countries that have used the N-Calculator model. About 69% of the Australia’s N footprint is attributed to food consumption and the associated food production, with the rest from energy consumption. Beef consumption and production is the major contributor of the high food N footprint, while the heavy dependence on coal for electricity explains the large energy N footprint. Our study demonstrates opportunities for managing Nr loss and lifestyle choices to reduce the N footprint.

More than half of the world’s population is nourished by food produced using synthetic nitrogen (N) fertilizers1,2. However, N escapes to the environment as reactive N (Nr; all species of N except N2) through different pathways during food and energy production and consumption3,4. With a large anthropogenic Nr creation rate and continued losses of Nr through human activities, increasing amounts of Nr are accumulating in the environment where they contribute to negative impacts. For example, the Nr-related damage in the European Union (EU) has been estimated at €70 billion to €320 billion per year5.

The N footprint is an index that assesses the total amount of Nr released to the environment as a result of an entity’s resource consumption6. It includes Nr losses from food production, food consumption, fossil fuel combustion for housing and transportation, and provision of goods and services. Using the N-Calculator model, the N footprint has been developed for many countries (i.e., United States, Netherlands, Germany, United Kingdom, Japan, Austria)6–11. This consumer-based tool can connect individual consumption choices with Nr losses and show how lifestyle choices affect these Nr losses. Using a different approach (a mass balance), N footprints have also been calculated in other countries such as China12. A Multi-Region Input-Output (MRIO) approach, which accounts for trade by tracking N losses through economic models, was used to calculate the N footprint for 188 countries13. However, compared to the N-Calculator, these approaches have less focus on consumers’ behavior.

While Australia and its products are often perceived as being ‘clean and green’4, it has unique challenges for managing Nr issues. Although Australia is the planet’s sixth largest country, it has a small population (24 million) with a low population density of 3 people/km2 compared to the global average of 49 people/km2 (ref. 15). However, 85% of Australia’s population is found in the coastal areas, resulting in higher environmental risk to the coastal habitats (e.g., Great Barrier Reef)15. Furthermore, more than half of Australia’s land is used for farming production, 90% of which is used for grazing in the arid and semi-arid zones16. The widespread use of agricultural land in Australia has led to issues such as mining soil N in dryland rain-fed wheat systems and excessive N use in feedlot animal production systems18,19. Although numerous studies have linked agricultural Nr to environmental problems20–22, the N footprint has not been quantified for Australia. The objectives of our study were therefore to: (1) assess the Nr loss driven by food and energy consumption and associated production in Australia using the N-Calculator model; (2) benchmark Australia’s performance of Nr loss against other countries; and (3) explore the driving forces and mitigation strategies for the Australia’s N footprint.

1Crop and Soil Science Section, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Victoria 3010, Australia. 2Department of Natural Resources & Earth Systems Science and The Sustainability Institute, University of New Hampshire, 107 Nesmith Hall, 131 Main Street, Durham, NH, 03824, USA. 3Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Road, P.O. Box 400123, Charlottesville, VA 22904-4123, USA. 4Department of Land Management, Zhejiang University, Hangzhou 310058, PR China. Correspondence and requests for materials should be addressed to D.C. (email: delichen@unimelb.edu.au)
Results

Per capita N footprint in Australia. The per capita N footprint in Australia was 47 kg N yr\(^{-1}\) in 2011. The food portion of the N footprint (32 kg N capita\(^{-1}\) yr\(^{-1}\)) was the largest component, of which 2 kg N capita\(^{-1}\) yr\(^{-1}\) was from food consumption after sewage treatment and 30 kg N capita\(^{-1}\) yr\(^{-1}\) from the associated food production. However, before being corrected for the amount of Nr converted to N\(_2\) or recycled during sewage treatment, the actual food consumption N was 5 kg N capita\(^{-1}\) yr\(^{-1}\) (Fig. 1a, Supplementary Table 1). 82% of the food N footprint is from animal products, half of which is from beef (Fig. 1b). For crop products, cereals represent the largest proportion (35% of the crop N footprint), followed by vegetables, potatoes, fruits and legumes (Fig. 1b). The energy sectors contribute 15 kg N capita\(^{-1}\) yr\(^{-1}\), which is made up of the housing (9 kg N capita\(^{-1}\) yr\(^{-1}\)), transportation (2 kg N capita\(^{-1}\) yr\(^{-1}\)), and goods and services (4 kg N capita\(^{-1}\) yr\(^{-1}\)) sectors (Fig. 1a, Supplementary Table 1). Almost half of the energy N footprint comes from electricity consumption (Fig. 1c).

Australia's virtual N factors (VNFs). There is a large variability in Australia's VNFs (a metric that describes the total Nr loss to the environment during food production per unit of N in the consumed food product\(^5\)), which range from 1.2 (legumes) to 29.8 (feedlot lamb) kg N released to the environment per kg N consumed (Table 1, Fig. 2, Supplementary Table 4). Generally, animal products' VNFs are larger than those of plant products. For plant products, the VNF is as low as 1.2 (legumes) and 1.8 (cereals), and as high as 8.0 (vegetables) and 9.4 (fruits). The VNF of animal products ranges from 0.6 for wild-caught seafood to 25.2 and 29.8 for feedlot beef and lamb respectively; other meat products have a VNF of around 5 (Table 1, Fig. 2, Supplementary Table 4).
Nr removal factor is 60% in Australia, 79% in Austria, 78% in the Netherlands, and 67% in Germany). VNFs because of low N use efficiency in these production systems 24,25, the Nr loss per serving of vegetables or fruits is the largest component of the total N footprint among all of the countries (69–92% of the total N footprint), and the amount of Nr loss associated with food production is the highest in Australia (30 kg N capita −1 yr −1). Beef production is the least efficient way of using N and supplying dietary protein in most countries that have completed their calculation of VNFs 6–9,23,39.

Discussion

Production methods affect the VNFs. Examples include wild-caught seafood (0.6) vs. farmed seafood (4.2), lamb from the grazing system (5.7) vs. feedlot system (29.8), and beef from grazing system (7.4) vs. feedlot system (25.2) (Fig. 2b, Supplementary Table 4). Australia’s feedlot production systems have a higher VNF than grazing production systems (Fig. 3). Although most of Australia’s sheep and cattle by count are grazing outdoors, the amount ofNr loss from the grazing system (5.7) vs. feedlot system (29.8), and beef from grazing system (7.4) vs. feedlot system (25.2) (Fig. 2b, Supplementary Table 4). Australia’s feedlot production systems have a higher VNF than grazing production systems (Fig. 3). Although most of Australia’s sheep and cattle by count are grazing outdoors, the feedlot systems contribute a large percentage of meat production. The Australian beef and lamb VNFs weighted by production are still higher than those of other countries.

Australia vs. other countries. At a global scale, Australia has the largest N footprint both in the food and energy sectors among the nine countries where the N footprint has been calculated using the N-Calculator model (Fig. 1a, Supplementary Table 1). Australia’s food N footprint is the largest because it has the highest rate of beef consumption and the highest beef VNF (Fig. 1a, Table 1, Supplementary Table 1). Australia’s energy N footprint is similar to that in other developed countries (US, 5 kg N capita −1 yr −1; Japan, 4 kg N capita −1 yr −1) but higher than that in less-developed countries (Tanzania; 2 kg N capita −1 yr −1). However, Australia and most of the developed countries use advanced wastewater treatment to recycle or convert Nr to N2, which substantially diminishes the discharge of Nr from food consumption to the environment (e.g. the Nr removal factor is 60% in Australia, 79% in Austria, 78% in the Netherlands, and 67% in Germany). For the energy sectors, Australia has the highest total energy N footprint (15 kg N capita −1 yr −1) among all countries, which is several times higher than the Netherlands, Austria, Japan, and Germany (2–4 kg N capita −1 yr −1) and even tenfold higher than Tanzania (1 kg N capita −1 yr −1) (Fig. 1a, Supplementary Table 1). Australia’s energy N footprint is the largest due to a heavy dependence on coal, which drives up its electricity N footprint.

Table 1. Comparisons of the virtual N factors (VNFs; units: kg N loss (kg consumed N)−1 yr−1) and N footprints (kg N capita−1 yr−1) for major food categories in Australia and other countries. *Japan without trade.

| Products | Cereals | Legumes | Potatoes | Vegetables | Fruits | Seafood | Egg | Poultry | Dairy | Pork | Lamb | Beef |
|----------|---------|---------|----------|------------|--------|---------|-----|---------|-------|------|------|------|
| Australia | 1.8 | 1.2 | 4.9 | 8.0 | 9.4 | 1.9 | 4.0 | 4.8 | 5.0 | 5.5 | 9.3 | 13.4 |
| US* | 1.4 | 0.5 | 1.5 | 9.6 | 9.6 | 4.1 | 3.2 | 3.2 | 4.3 | 4.4 | 5.2 | 7.9 |
| UK | 1.3 | 0.5 | 1.1 | 8.2 | 8.2 | 2.9 | 3.2 | 3.2 | 3.9 | 4.4 | 5.2 | 7.9 |
| Austria9 | 1.2 | 0.4 | 2.0 | 4.3 | 4.3 | — | 2.5 | 2.5 | 3.7 | 3.6 | 3.8 | 5.4 |
| Japan9 | 3.3 | 2.8 | 6.1 | 4.6 | 4.6 | 1.7 | 10.7 | 10.7 | 3.9 | 12.9 | 5.6 | 27.3 |
| Tanzania23 | 6.3 | 0.3 | 1.8 | 4.1 | 4.1 | 0.2 | 0.5 | 0.8 | 8.3 | 3.3 | 3.3 | 7.0 |

| Nitrogen consumption |
|----------------------|
| Australia | 0.86 | 0.13 | 0.08 | 0.11 | 0.04 | 0.21 | 0.10 | 0.78 | 0.94 | 0.27 | 0.19 | 0.77 |
| US | 0.98 | 0.11 | 0.10 | 0.11 | 0.05 | 0.19 | 0.20 | 0.92 | 1.10 | 0.37 | 0.01 | 0.63 |
| UK | 1.21 | 0.08 | 0.18 | 0.14 | 0.06 | 0.26 | 0.16 | 0.62 | 1.04 | 0.37 | 0.08 | 0.33 |
| Austria | 1.15 | 0.03 | 0.10 | 0.15 | 0.08 | 0.18 | 0.21 | 0.40 | 1.12 | 0.93 | 0.02 | 0.35 |
| Japan | 1.01 | 0.06 | 0.04 | 0.17 | 0.03 | 0.89 | 0.30 | 0.34 | 0.39 | 0.28 | 0.01 | 0.18 |
| Tanzania | 1.25 | 0.65 | 0.21 | 0.07 | 0.08 | 0.10 | 0.01 | 0.02 | 0.18 | 0.01 | 0.03 | 0.12 |

| Nitrogen footprints |
|---------------------|
| Australia | 2.41 | 0.28 | 0.47 | 1.03 | 0.42 | 0.61 | 0.52 | 4.54 | 5.66 | 1.78 | 1.93 | 11.07 |
| US | 2.36 | 0.17 | 0.25 | 1.22 | 0.51 | 0.94 | 0.86 | 3.88 | 5.81 | 2.02 | 0.05 | 5.60 |
| UK | 2.77 | 0.12 | 0.39 | 1.29 | 0.59 | 1.00 | 0.69 | 2.62 | 5.11 | 1.99 | 0.49 | 2.98 |
| Austria | 2.53 | 0.04 | 0.31 | 0.79 | 0.41 | — | 0.75 | 1.40 | 5.26 | 4.29 | 0.09 | 2.24 |
| Japan | 4.35 | 0.21 | 0.27 | 0.95 | 0.15 | 2.40 | 3.49 | 4.02 | 1.92 | 3.93 | 0.02 | 5.00 |
| Tanzania | 9.14 | 0.85 | 0.59 | 0.35 | 0.40 | 0.12 | 0.02 | 0.04 | 1.66 | 0.02 | 0.11 | 0.98 |
Figure 2. Nitrogen uptake (%) and virtual N factors (VNF) in Australia for the main food commodity groups by each step of the food production chain. (a) Vegetable products; (b) Animal products.

Figure 3. Reactive nitrogen (Nr) flows along the entire beef production and consumption chain in Australia. This explains the process used to calculate Nr flow in (a) a grazing system, starting with 100 units of new Nr; and (b) a feedlot system, starting with 100 units of new Nr. Notes: (1) The dark red boxes show the available Nr at each stage of the food production and consumption, with the numbers reflecting the magnitude of Nr; (2) The black arrows show the Nr that makes it to the next stage; (3) The brown arrows show the Nr that releases to the environment; (4) The light red boxes show the Nr loss at each stage of the food production and consumption, with the numbers reflecting the magnitude of Nr loss; (5) The transparent red boxes with number show the total Nr loss by all stages of food production and consumption; (6) The green dotted arrows show the Nr recycled; (7) The transparent green boxes with number show the amount of recycled Nr which is subtracted from the Nr wasted to find the actual Nr lost to the environment; (8) The blue arrows show the consumed Nr that is converted to N₂ or recycled during sewage treatment; (9) The transparent blue boxes with number show the amount of consumed Nr that is converted to N₂ or recycled during sewage treatment; and (10) The diagrams show the summation of multiple iterations of the calculations; the iterations determine how recycled Nr is distributed throughout the system.
beef resulted in Australia having the largest beef N footprint (11.1 kg N capita$^{-1}$ year$^{-1}$) of the main contributor. Beef consumption by Australia’s people is more than double and four times larger than the US (Fig. 1a, Supplementary Table 1). 72% of N consumption in Australia is from animal food (Table 1), and beef is the main contributor. Beef consumption by Australia’s people is more than double and four times larger than the consumption by the British and the Japanese, respectively (Table 1). The high consumption level and high VNF of beef resulted in Australia having the largest beef N footprint (11.1 kg N capita$^{-1}$ yr$^{-1}$), which is much greater than that in other countries (Table 1). As studies have shown how food choices and diet changes can reduce the N emission in the European Union$^{32,33}$, choosing a diet better aligned with the Australia dietary guidelines would both reduce Australia’s N footprint and improve consumers’ health.

Australia has a large land area with low rainfall and fertility, both of which promote the long tradition of grazing cattle. About 97–98% of 28 million cattle in Australia are located in extensive native grasslands$^{34}$, which receive little or no fertilizer N. Although the N feed conversion ratio by feedlot cattle (14%) is higher than cattle in extensive grazing farms (7–10%)$^{37,38}$, we found that 79% of N excreted by grazing cattle will return to the grassland whereas only 15% of N excreted from feedlot cattle will be collected and reused (Fig. 2b, Fig. 3, Supplementary Fig. 1, Supplementary Table 4). In particular, ammonia (NH$_3$) emissions from the grazing system are estimated at 0.2 kg NH$_3$-N/kg manure N$^{39}$ but 0.81 kg NH$_3$-N/kg manure N in the feedlots$^{31,36}$. That means that when producing the same amount of beef, more N is released to the environment from feedlot systems than from grazing farms. Likewise, the comparisons between grazing versus feedlot lamb and wild-caught versus farmed seafood also indicate that the extensive food production systems in Australia release less N than the intensive ones (Fig. 2b, Supplementary Fig. 1, Supplementary Table 4). Around two thirds of total Australia’s agricultural products are exported worldwide with an international reputation for clean and green production$^{40}$. In particular, the relatively mild climate enables livestock to graze year-round$^{41}$, which supports protein-rich diets in Australia and helps to produce large exportable food surpluses (e.g., Australia is the second largest exporter of beef in the world)$^{42}$.

Australia also has abundant energy resources. Due to the plentiful resources and low-cost production$^{43}$, 69% of electricity was generated from coal during 2012–2013, which was higher than any other developed country (e.g., 43% in the US and 29% in the UK)$^{44}$. We demonstrated that Australia emitted about 7.5 kg N capita$^{-1}$ yr$^{-1}$ from electricity generation in 2011, compared to 3.7 and 1.8 kg N capita$^{-1}$ yr$^{-1}$ for the US and the UK, respectively. The high N emissions associated with electricity generation concomitantly contributed to a larger N footprint for goods and services in Australia (Fig. 1a, Supplementary Table 1). The high transportation N footprint is caused by the low housing density and long distances of daily travel in Australia, as well as the less stringent regulations on energy efficiency, vehicle emissions and carbon pricing than other developed nations such as the US and the UK$^{45}$. However, Australia has a rich diversity of renewable energy resources (wind, solar, geothermal, hydro, wave, tidal, bioenergy), the wide adoption of these renewable resources would decrease the energy component of the N footprint.

The unexpectedly large Australian N footprint has not been uncovered until now. Our results show that lifestyle choices (especially beef consumption and coal for electricity) have major impacts on N losses to the environment. Consumers could reduce their N footprint by choosing a diet with less meat and using more renewable energy. The on-farm N footprint can be reduced by improving farm N use efficiency, such as by the 10 “Key Actions” listed in “Our Nutrient World”$^{46}$. These strategies are critical for meeting the increasing demand for food and energy in an environmentally sustainable way.

**Materials and Methods**

**Study area.** This consumer-based study accounts for the all domestic consumption and the associated production of food and energy in Australia. Given this consumer focus, this study does not account for the N footprint of exports. We also assumed that all food and energy were produced using Australia’s production methods and therefore did not account for the effects of imports. The N footprint was divided into food, housing, transportation and goods & services, and each sector was further divided into subsectors to cover the major human activities related to N loss.

**N footprint calculation.** We followed the methodology of the N-Calculator model proposed by Leach et al.$^{4}$, which was also adopted by the Netherlands$^{6}$, Germany$^{9}$, UK$^{1}$, Austria$^{2}$, Japan$^{1}$, and Tanzania$^{18}$. For the food component of the N footprint, we estimated the N losses to the environment along the food production and consumption chain, starting with N fertilizer applied to cropland and ending with sewage treatment. The food N footprint has two parts: the food consumption N footprint and the associated food production N footprint. Food consumption was calculated by subtracting food waste from the Australia’s food supply$^{28}$. The food consumption N was assumed to be completely excreted since adults generally do not accumulate N in their body$^{47}$. Nonetheless, the widespread use of advanced sewage treatment in Australia removes 60% of this N from
the sewage stream by either converting it into a non-reactive form (N₂) or recycling and reusing it in the form of sludge. The N removal from the sewage stream is considered a reduction to the food consumption footprint. The associated food production footprint accounts for all N lost during the food production process. The food production N footprint is calculated using virtual N Factors (VNFs), which are defined as the total N loss to the environment during production per unit of N in the final consumed food products. Examples of these N losses include the fertilizer N not incorporated into the plant, feed N not retained in the animal products, crop residues N not recycled, and processing and food waste N. Food production N is calculated by multiplying the VNF by the food N consumed; the VNFs covers all steps from initial fertilizer application to final food consumption. We calculated Australia’s VNFs for 12 major food categories: cereals (weighted-average of rice, wheat, barley, sorghum), legumes, potatoes, vegetables, fruits, seafood (weighted-average of wild-caught and farmed), poultry, egg, dairy products (weighted-average of milk, cheese, yoghurt and dry milk), pork, lamb and beef (weighted-average of grazing and feedlot systems) (see Supplementary Table 4, Supplementary Fig. 1 for N flow along the food production and consumption chain).

N losses associated with energy use during food production (e.g., on-farm energy use, food processing, packaging, transportation) were also included as part of the food N footprint. We used an environmentally extended input–output analysis (EEIO) to allocate Australia’s total NOₓ and NH₃ emissions associated with food production to various food categories.

The energy component of the N footprint consists of four main aspects of daily life associated with energy consumption: housing (e.g., electricity, natural gas use), transportation (e.g., plane, train, car), goods (e.g., clothing, furniture, tools) and services (e.g., education, insurance and financial services). A bottom-up approach was adopted to calculate the N footprint for major areas of N consumption (electricity, heating, personal travel). For these sectors, activity data (e.g., hours flown by aircraft) was used with an emission factor (e.g., amount of N emitted per hour flying) (see Supplementary Table 3 for data and references). A top-down approach (EEIO analysis for emissions of N from NOₓ and NH₃ within Australia) was used to calculate the N footprint of the remaining sectors related to consumers. After removing any double-counting of fuel sources, the sum of the bottom-up and top-down footprints is the total energy N footprint.

Data sources. Key sources of data for the N footprint included: International statistical data sources; Australia’s governmental statistical data sources; industry data sources; data from a number of published articles for some coefficients; consultation with industry, researchers, and other experts in the field (Supplementary Tables 2, 3 and 4).

References
1. Erisman, J. W., Sutton, M. A., Galloway, J., Klömint, Z. & Winiwarter, W. How a century of ammonia synthesis changed the world. Nature Geoscience. 1, 636–639 (2008).
2. Zhang, X. et al. Managing nitrogen for sustainable development. Nature. 528, 51–59 (2015).
3. Erisman, J. W. et al. Consequences of human modification of the global nitrogen cycle. Philosophical Transactions of the Royal Society of London B: Biological Sciences. 368, 20130116 (2013).
4. Galloway, J. N. et al. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science. 320, 889–892 (2008).
5. Sutton, M. A. et al. The European Nitrogen Assessment: Sources, Effects And Policy Perspectives. (Cambridge University Press, 2011).
6. Leach, A. M. et al. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environmental Development. 1, 40–66 (2012).
7. Stevens, C. J., Leach, A. M., Dale, S. & Galloway, J. N. Personal nitrogen footprint tool for the United Kingdom. Environmental Science: Processes & Impacts. 16, 1563–1569 (2014).
8. Shibata, H., Cattaneo, L. R., Leach, A. M. & Galloway, J. N. First approach to the Japanese nitrogen footprint model to predict the loss of nitrogen to the environment. Environmental Research Letters. 9, 115013 (2014).
9. Pierer, M., Winiwarter, W., Leach, A. M. & Galloway, J. N. The nitrogen footprint of food products and general consumption patterns in Austria. Food Policy. 49, 128–136 (2016).
10. Galloway, J. N. et al. Nitrogen footprints: past, present and future. Environmental Research Letters. 9, 115003 (2014).
11. Gonçalves, V. M. P. Impact of nitrogen into the environment. A step on nitrogen footprint calculation in Lisbon, Portugal (in review).
12. Gu, B. et al. Nitrogen footprint in China: food, energy, and nonfood goods. Environmental science & technology. 47, 9217–9224 (2013).
13. Oita, A. et al. Substantial nitrogen pollution embedded in international trade. Nature Geoscience. 9, 111–115 (2016).
14. Chang, H. S. C. & Kristiansen, P. Selling Australia as ‘clean and green.’ Australian Journal of Agricultural and Resource Economics. 50, 103–113 (2006).
15. USCB. U.S. and World Population Clock http://www.census.gov/popclock/world (Date of access: 17/7/2016) (2016).
16. Death, G., Fabricius, K. E., Sweatman, H. & Puotinen, M. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proc Natl Acad Sci USA 109, 17995–17999, doi: 10.1073/pnas.1208909109 (2012).
17. FAOSTAT. Food and Agriculture Organization of the United Nations Statistical Databases, Inputs-Land Sheet http://faostat3.fao.org/download/R/RL/E (Date of access: 5/12/2015) (2016).
18. Hochman, Z. et al. Prospects for ecological intensification of Australian agriculture. European Journal of Agronomy. 44, 109–123 (2013).
19. Stott, K. J. & Gourley, C. J. P. Intensification, nitrogen use and recovery in grazing-based dairy systems. Agricultural Systems. 144, 101–112, doi: 10.1016/j.agsy.2016.01.003 (2016).
20. Larn, S. K. et al. Measurement and mitigation of nitrous oxide emissions from a high nitrogen input vegetable system. Scientific reports. 5 (2015).
21. Chen, D. et al. A new cost-effective method to mitigate ammonia loss from intensive cattle feedlots: application of lignite. Scientific reports. 5 (2015).
22. Wiedemann, S. G. et al. Resource use and greenhouse gas intensity of Australian beef production: 1981–2010. Agricultural Systems. 133, 109–118, doi: 10.1016/j.agsy.2014.11.002 (2015).
23. Hutton, O. et al. Toward a nitrogen footprint calculator for Tanzania. Environ. Res. Lett (in review).
24. Harper, S. Environmental effects of vegetable production on sensitive waterways. (2014).
25. Hippler, F. W. R. et al. Uptake and Distribution of Soil Applied Zinc by Citrus Trees—Addressing Fertilizer Use Efficiency with 68 Zn Labeling. PloS one. 10, e0116903 (2015).
Beef and coal are key drivers of Australia’s high nitrogen footprint.

How to cite this article

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Liang, X. et al. Beef and coal are key drivers of Australia’s high nitrogen footprint. Sci. Rep. 6, 39644; doi: 10.1038/srep39644 (2016).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
