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1 **Environmental impact of fertiliser embodied in a wheat-to-bread** 2 **supply chain**

3
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10
11 **Food production and consumption cause approximately one third of total greenhouse**
12 **gas emissions¹⁻³, and therefore delivering food security challenges not only the capacity**
13 **of our agricultural system but also its environmental sustainability⁴⁻⁷. Knowing where**
14 **and at what level environmental impacts occur within particular food supply chains is**
15 **necessary if farmers, agri-food industries and consumers are to share responsibility to**
16 **mitigate these impacts^{7,8}. Here we present the analysis of a complete supply chain for a**
17 **staple of the global diet – a loaf of bread. We obtained primary data for all the processes**
18 **involved in the farming, production and transport systems leading to the manufacture**
19 **of a particular brand of 800g loaf. The data were analysed using an advanced life-cycle**
20 **assessment tool⁹, yielding metrics of environmental impact, including greenhouse gas**
21 **emissions. We show that over half the environmental impact of producing the loaf of**
22 **bread arises directly from wheat cultivation, the use of ammonium nitrate fertiliser**
23 **alone accounting for around 40%. These findings reveal the dependency of bread**
24 **production upon the unsustainable use of fertiliser and illustrate the detail needed if the**

1 **actors in the supply chain are to assume shared responsibility for achieving sustainable**
2 **food production.**

3
4 A projected human population of 10 billion¹⁰ and an increasing consumption of food
5 that has high environmental impact associated with economic development¹¹ are placing
6 massive strain on the global agri-food system. Meeting the challenge of achieving
7 sustainable food security requires consideration of all the key aspects of food production and
8 consumption, taking a holistic agri-food ecosystem approach that includes land and resource
9 use, crop production, consumer behaviour and human health⁷. Moreover, in order to
10 materialise a condition in which collective action and shared responsibility occurs within
11 fragmented food supply chains, an integrating framework that involves the mapping, analysis,
12 visualisation and sharing is needed⁷. Integration can be enabled through supply chain
13 sustainability research, which yields total visibility of the entire supply chain^{9,12,13}. To realise
14 this ambition, a natural resource driven business experiment involving a mixed methods
15 approach of quantitative analytical modelling and qualitative contextualisation was deployed
16 to develop a detailed case study of environmental impact in the manufacture of a specific
17 food-stuff – a loaf of whole grain bread. This involved Life Cycle Assessment (LCA) at each
18 stage of the supply chain for the loaf of bread.

19 It is well known that the more precise are the sources of data for an LCA model, the
20 more accurate are the results from the LCA modelling. Most of the existing LCA research
21 relies on both primary and secondary data, the latter used to compensate for the unavailability
22 of primary data. Consequently, an artificial level of uncertainty in the data averages out the
23 variation hence making the environmental impact from a modelled supply chain a proxy and
24 an estimate, as in all previous LCA of the wheat-bread supply chain¹⁴⁻¹⁷, where primary data
25 might be used for one process stage but secondary data for others (e.g. ref. 17). To address

1 this deficiency, and in contrast to all previous studies, we utilised primary data at all stages of
2 the linked Cradle to Gate UK bread manufacturing life cycle, with 90% of the process stages
3 modelled on the basis of primary data. This was enabled by collaboration with a commercial
4 bread and flour producer and a large agronomy services provider. The higher level of
5 granularity achieved in this way increases the confidence level of the results and therefore the
6 certainty and validity of the conclusions upon which action is based.

7 Three supply chain stages were considered (Figure 1): **wheat cultivation** which
8 includes ground preparation, sowing the wheat seed, application of agrochemicals,
9 harvesting of the wheat grain, drying, storage and finally transportation to the mill; **milling**,
10 which includes the transformation of cultivated wheat grain into wholemeal flour, through
11 intake, cleaning, milling and out-loading processes, prior to transportation to the bakery; and
12 **baking**, which comprises all the remaining processes leading to the final, packaged loaf of
13 wholemeal bread. Primary data for material and energy flow was collected for the designated
14 14 processes at these three stages of the supply chain, calibrated to a functional unit, a single
15 wholegrain loaf of bread, weighing 800 g (Supplementary Data Figs.1-3). Each loaf required
16 cultivation of 7.2E-05 hectares or 0.72 m² of land. This produced 688 g of grain, using a
17 number of fertiliser inputs: 42.0 g of granular ammonium nitrate (580 kg/hectare), 11 g of
18 triple superphosphate (152 g/hectare), 6 g muriate/sulphate of potassium (83 kg/hectare) and
19 3 mL of liquid ammonium nitrate (42 L/hectare, applied just prior to harvest to maximise
20 protein content of the grain). Upon transfer to the mill there are two key output streams.
21 Firstly, a small proportion of the grain (about 3%) is rejected upon delivery if it fails to meet
22 strict quality standards concerning excess moisture, the presence of foreign bodies or
23 contamination. Secondly, around 22% of wheat grain is lost during the extraction process;
24 this loss accounts for the difference between in mass between raw, dirty wheat and flour
25 leaving, after excess moisture and non-millable impurities are removed. During milling a

1 total of 520 g of flour is produced in processes consuming approx. 0.07kWh electricity.
2 Before baking a number of ingredients, including 365 g of water and 13 g of sugar, were
3 added to the flour to give a mass of 950 g. A further 5.8 % loss of solid flour due to sub
4 optimal quality reduced this mass to 898 g, whilst the final preparation and the baking
5 process resulted in 3.5 g of flour loss and reduction in mass to 807 g through water
6 evaporation. 0.09 kWh of electricity was consumed at the bakery.

7 The raw data were analysed using the Supply Chain Environmental Analysis Tool's
8 (SCEnAT) Life Cycle Assessment (LCA) methodology⁹. To provide a broad assessment of
9 environmental impact on air, water and land, six contrasting impact categories were selected
10 for analysis – these are expressed as “potential” impacts. Thus, for example, emission of
11 greenhouse gases is quantified as global warming potential (GWP), the eutrophication
12 potential (EP) is a measure of pollution of water courses and human toxicity potential (HTP)
13 quantifies the potential human health problems caused by release of toxic substances into the
14 environment.

15 GWP data calculated for each supply chain process are shown in supplementary data,
16 figures 3-6. GWP from the whole supply chain was found to be 0.589 kg CO₂-eq per loaf of
17 bread, and it is clear immediately that wheat cultivation is the major source - this supply
18 chain stage totalling 0.388 kg CO₂-eq, with the growth and protection process stages (mostly
19 fertiliser) alone accounting for 0.281 kg CO₂-eq. Milling added a further 0.028 kg CO₂-eq.
20 and the bakery stage 0.173 kg CO₂-eq.

21 Impacts from each process in the supply chain were added together to give their
22 cumulative environmental impacts, expressed as a percentage of the total in Figure 2. All the
23 processes involved in cultivation of wheat account for 65.8 % of the total GWP, which is
24 within the range of previous analyses using secondary datasets¹⁴⁻¹⁶. Similarly, wheat
25 cultivation was the principle cause of the other environmental impacts: 68.5 % EP, and 77.9

1 % HTP. Fertiliser used to promote growth of the wheat crop was found to be the largest
2 single process contributing to environmental impact metrics (red bar in Fig. 2), for example
3 accounting for 47.8 % GWP, 38.5% EP and 41.9 % HTP.

4 Other processes involved in cultivation had significant, though lesser impacts. The
5 use of farm machinery in preparation of land accounts for 5.2 % of total GWP. Grain drying
6 is another significant cultivation hotspot; farmers are normally contracted to deliver wheat
7 grain for storage with a water content of lower than 15% in order to pass the weight and
8 pricing thresholds expected by the buyers. In our study, electric continuous flow grain dryers
9 were used to reduce water content. Grain drying, storage and transport to the mill together
10 account for 8.7 % of GWP, 6.5 % of EP and 7.6 % of HTP respectively.

11 Baking, ingredients handling and cleaning/milling were found to be significant GWP
12 hotspots, accounting for 9.7, 9.1 and 4.4 % respectively. Energy is the key contributor to
13 GWP in milling and baking processes. In particular, gas usage during baking accounted for
14 7.9 % of overall GWP. Similarly, electricity usage during cleaning/ milling, mixing/ divide/
15 first proof, baking and de-pan/ cooling stages were identified as significant hotspots,
16 contributing 4.2 %, 1.6 %, 1.8 % and 2.2 % to overall GWP respectively. These processes
17 contribute to ET and HTP to similar extents.

18 The upstream supply chains of various ingredients added to flour to form bread dough
19 during the ingredients handling stage of baking also contributed to GWP, the most significant
20 being wheat gluten, sodium stearoyl lactylate, fermented wheat flour and sugar which
21 accounted for 2.6 %, 1.5 %, 1.5 % and 1.1 % respectively. The switch to the use of Low
22 Density Polyethylene (LDPE) wrapping has reduced the environmental burden of bread
23 packaging, as compared to more traditional plastic packaging types. However, packaging is
24 still a notable contributor to GWP (3.1 %).

1 This study highlights the contribution of fertiliser to the environmental impact of
2 bread production. Remarkably, the use of ammonium nitrate fertiliser alone accounts for
3 most of this, 0.256 kg CO₂-eq, 43.4 % of overall GWP (Figure 3). Similarly 34.1 % of EP
4 and 32.5% of HP are due to ammonium nitrate. This value of GWP measures the CO₂
5 emissions associated with the manufacture and application of the fertiliser and N₂O released
6 into the atmosphere from the on-farm degradation of ammonium nitrate by soil microbes.

7 The exact amount of GWP from N₂O release depends of a variety factors and its
8 estimation is the subject of some controversy¹⁸. Previous studies with maize¹⁹ and wheat²⁰
9 have estimated it to be of similar proportions to the GWP arising from energy use during
10 manufacture. We calculated 0.083 kg CO₂e per loaf arising from N₂O emissions (see
11 supplementary data Figure 4), approx. 1/3 of the total. The other environmental impacts of
12 the use of this fertiliser have been described²¹, eutrophication of water courses in particular.
13 Their quantitative significance in the wheat-to-bread supply chain is made clear in our study.

14 Nitrogen use efficiency (NUE) of wheat yield, defined as the ratio of harvested
15 nitrogen to that applied to the field ultimately determines the environmental impact of
16 nitrogen fertiliser. In our study NUE was estimated to be 71%, in line with that predicted for
17 the 246 kg N/hectare fertiliser application used²², which is slightly above the UK average,
18 and typical of intensified production. Studies show that whilst wheat yield increases with
19 higher applications of fertiliser, NUE declines²². However, without such intensive
20 fertilisation, there is lower yield, and a small but important reduction in the protein content of
21 the grain. Consequently, the cost of a staple food item made from UK wheat could rise.
22 Alternatively, in a global wheat market, the environmental impact of fertiliser use could be
23 exported via the import of cheaper grain from other countries. Clearly neither of these
24 scenarios are desirable – instead new solutions are needed²³. These solutions can take place

1 at different parts of the extended supply chain, from fertiliser manufacture to bread
2 consumption.

3 More energy efficient methods of synthesising ammonium nitrate fertiliser would be
4 beneficial (but presently seem unlikely), as would be a shift towards carbon neutral energy
5 supply. But the most immediate solutions to the fertiliser problem mostly reside in increasing
6 NUE whilst maintaining high yield²¹, through a combination of improved agronomic practice
7 and improved crop plant physiology. To reduce on-farm fertiliser use, there needs to be a
8 move away from blanket fertiliser application towards area-specific and temporal-specific
9 application of fertiliser²³, acknowledging the soil variation across different parts of the crop
10 field and the differing physiological requirements for nitrogen at different stages of crop
11 growth. More radical is a shift away from chemical fertiliser altogether towards a biological
12 approach to nitrogen fertilisation, such as crop rotations with nitrogen-fixing legumes²⁴ and
13 restoration of the soil microbe/plant root interactions that promote plant growth²⁵. In fact,
14 judicious use of fertiliser incorporated into a series of such modified agronomic practice
15 drastically reduced GWP of wheat cultivation in Canada²⁰. Development of new wheat
16 varieties with an increased intrinsic NUE could also make a significant contribution, although
17 there are significant challenges to achieving this goal²⁶ – either an increased ability to take up
18 nitrogen from the soil²⁷ or an altered physiology which allows more biomass accumulation
19 per unit of taken-up nitrogen²⁸ and allocation of more biomass N to the grain²⁹. Biological
20 nitrogen fixation by the wheat plant itself remains an important, if elusive goal³⁰. One
21 possible consequence of maintaining wheat yield whilst reducing or eliminating fertiliser use
22 could be a reduction in the protein content of the wheat grain. At present, the protein content
23 of wheat grain used in flour production forms a key aspect of the commercial contract. For
24 UK bread-making, a high protein content of 11-13g/100g is required, a higher amount needed
25 for wholemeal loaves (which account for approx. 10% of the UK market) compared to white

1 **loaves (80% UK market).** The wheat grain protein requirement for wholemeal bread in the
2 current study is 13g/100g. An important part of the solution to the fertiliser problem could be
3 a change in bread-making technology to accommodate grain with lower protein content³¹.

4 Much research takes a generic approach to identifying the interventions needed to
5 deliver sustainable food security. Extending beyond this, our study points to the increased
6 granularity of the information that is required to make accurately informed decisions about
7 individual food supply chains. As argued previously this information has to be integrated and
8 applied across the entire supply chain⁷ – otherwise time, effort and resources will be wasted
9 implementing changes of little overall significance whilst ignoring the real problem, in this
10 case study, the use of fertiliser. So, having identified the problem, responsibility for
11 implementing any or all of the above solutions must be designated. According to the
12 principles of extended producer responsibility, all the actors in the supply chain have to share
13 responsibility⁸. Similarly such responsibility must be extended to the consumer. Thus
14 although the fertiliser manufacturer may bear the biggest responsibility, actions have to be
15 co-ordinated across the wheat-bread supply chain, between the fertiliser manufacturer, the
16 farmer, the mill, the bakery, the retailer and the consumer. This new direction is feasible due
17 to increasingly advanced data capture and sensor technology where LCA will be a norm for
18 all decision making across the supply chains.

19 The dependency of delivering high yields of high protein bread wheat upon
20 unsustainable amounts of fertiliser exposes an unresolved grand challenge for the 21st
21 century: how to produce more food but with lower pollution³². Our findings bring into focus
22 a key part of this challenge – resolving the major conflict embedded in the agri-food system,
23 whose primary purpose is to make money not to provide sustainable global food security³³.
24 High agricultural productivity, necessary for profit for farmers, agri-businesses and food
25 retailers, whilst also keeping prices low for consumers, currently requires high levels of

1 application of relatively cheap (and often subsidised) fertilisers. The environmental impact
2 of fertiliser use is not costed within the system and thus, there are currently no effective
3 incentives to implement of any of the solutions described above³².

4

5 **Methods**

6 **Data collection.** A Life Cycle Assessment (LCA) methodological approach was used to
7 evaluate the environmental impact of commercial bread production in the UK, using 100%
8 group 1 and 2 domestic milling wheat. The functional unit is defined as a single wholegrain
9 loaf of bread, weighing a total of 800g and the scope of the study is from cradle (farm) to gate
10 (shipping of the final, packaged loaf of bread to a retailer). All agricultural and production
11 stages are based in the UK and data is representative of the 2014 wheat harvest and
12 production period. The supply chain was segmented into three distinct stages, cultivation,
13 milling and baking. Primary data was collected at each of these stages, with a leading UK
14 commercial bread manufacturer providing access to milling and bakery datasets and a large
15 agronomy organisation providing access to farm level data, using the example of a farm
16 producing UK group 1 and 2 milling wheat at 9.5t/ha. Data collection was undertaken
17 through both field interviews and analysis of organisational datasets, which in combination
18 provided researchers with a detailed understanding of energy and material flows through each
19 of the defined three model stages. For mill and bakery stages, data was obtained for two
20 specific sites that represented an average energy and material consumption balance for the
21 partner's annual production; these were in Bradford and Manchester respectively. At a farm
22 level, material, machinery and energy data, provided in collaboration with a large agronomy
23 organisation, has been modelled from an upper quartile farm in terms of yield and
24 agricultural efficiency.

1 **Environmental Impact Categories.** Life Cycle Inventory (LCI) data for all identified
2 material and flows was sourced from the Ecoinvent database (v3.2)³⁴. The Ecoinvent
3 database provides well-documented LCI process data for a large number of materials and
4 products covering relevant environmental flows, such as resource extraction, land use and
5 emissions, as well as all material and energy inputs and products of an activity. To provide a
6 broad assessment of the environmental impact that UK commercial bread production has to
7 air, water and land, six impact categories were selected for analysis from the CML (2001)
8 categorisation model available in Ecoinvent, produced by the Institute of Environmental
9 Sciences at Leiden University, NL³⁵. These are; Acidification Potential (kg SO₂-Eq – Eur
10 Average), Climate Change (kg CO₂-Eq – GWP 100a) and Eutrophication Potential (kg NO_x-
11 Eq – Eur Average). The various toxicity indicators use the reference unit, kg 1,4-
12 dichlorobenzene equivalent (1,4-DCB) and are: Freshwater Aquatic Eco-Toxicity (kg 1,4-
13 DCB-Eq – FAETP 100a), Freshwater Sediment Toxicity (kg 1,4-DCB-Eq – FSTP 100a) and
14 Human Toxicity (kg 1,4-DCB-Eq – HTP100a).

15 **Data Analysis.** Domestic LCI data was prioritised for material and energy flows throughout
16 the three stages where available. However, it was necessary to use European or global
17 reference LCI data for some inputs. Moreover, where specific LCI data was not obtainable
18 for a given material or process, appropriate ‘closest match’ substitutes were identified, in
19 collaboration with industry partners whenever possible. Allocation was necessary at both mill
20 and bakery stages, where for example, several types of flour are produced at the same mill or
21 energy flows are measured across multiple processes. Again, as with data substitution, where
22 necessary, allocation was carried out through dialogue with industry partners to maximise
23 accuracy. Our analysis considers output from milling and bakery stages as co-products, rather
24 than traditional wastes as they are sold for use in other industries. Due to the varied use of
25 these outputs, coupled with fluctuating market pricing, we did not consider economic

1 allocation to be appropriate in the instance. Instead, a traditional mass allocation approach
2 was adopted in keeping with the finding that for external communication to the market and
3 consumers, mass allocation should be viewed as the preferred method in most cases³⁶.

4 Data was combined and analysed using the Supply Chain Environmental Analysis Tool
5 (SCEnAT) developed by researchers at the University of Sheffield, UK. SCEnAT employs
6 life cycle assessment methodology⁹ to assess product supply chains, capturing both direct and
7 indirect/embodied emissions in accordance with ISO14040³⁷ and ISO14044³⁸ standards.
8 Nitrogen use efficiency was calculated using the quality-control grain protein content used by
9 the manufacturer and a wheat grain nitrogen/protein conversion factor of 5.81³⁹. On farm
10 N₂O emissions were calculated using established protocols^{40,41} as summarised in reference
11 42.

12 **Data availability.** The authors declare that the data supporting the findings of this study are
13 available within the paper and its supplementary information files

14

- 15 1. Garnett, T. Where are the best opportunities for reducing greenhouse gas emissions in the
16 food system (including the food chain)? *Food Policy* **36**, 523-532 (2011).
- 17 2. Tubiello, F.N. *et al*, The Contribution of agriculture, forestry and other land use activities
18 to global warming, 1990-2012. *Glob. Chang. Biol.* **21**, 2655-2660 (2015).
- 19 3. Vermeulen S.J., Campbell, B.M. & Ingram, J.S.I. Climate change and food systems. *Ann.*
20 *Rev. Enviro. Resource* **37**, 195-222 (2012).
- 21 4. Tilman, D. *et al*. Agricultural sustainability and intensive production practices. *Nature*
22 **418**, 671-677 (2002).
- 23 5. Godfray, H.J.C. *et al*. Food security: the challenge of feeding 9 billion people. *Science*
24 **327**, 812-818 (2010).

- 1 6. Foley, J.A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337-342 (2011).
- 2 7. Horton, P., Koh, S.C.L. & Shi Guang, V. An integrated theoretical framework to enhance
3 resource efficiency, sustainability and human health in agri-food systems. *J. Cleaner*
4 *Prod.* **120**, 164-169 (2016).
- 5 8. Lenzen, M., Murray, J., Sack, F & Wiedmann, T. Shared producer and consumer
6 responsibility – theory and practice. *Ecol. Econ.* **62**, 27-42 (2007).
- 7 9. Koh, S. *et al.* Decarbonising product supply chains: design and development of an
8 integrated evidence-based decision support system - the supply chain environmental
9 analysis tool (SCEnAT). *Int. J. Prod. Res.* **51**, 2092-2109 (2013).
- 10 10. United Nations. *World population prospects: the 2010 revision, highlights.* (Population
11 Division of the Department of Economic and Social Affairs of the United Nations
12 Secretariat, New York 2010).
- 13 11. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health.
14 *Nature* **515**, 518-522 (2014).
- 15 12. O'Rourke, D. The science of sustainable supply chains. *Science* **344**, 1124-1127 (2014).
- 16 13. Hellweg, S. & Canals, L.M. Emerging approaches, challenges and opportunities in life
17 cycle assessment. *Science* **344**, 1109-1113 (2014).
- 18 14. Jenson, J.K. & Arlbjørn, J.S. Product carbon footprint of rye bread. *J. Cleaner Prod.* **82**,
19 45-57 (2014).
- 20 15. Kulak, M. *et al.* Life cycle assessment of bread from several alternative food networks in
21 Europe. *J. Cleaner Prod.* **90**, 104-113 (2015).
- 22 16. Espinoza-Orias, N., Stichnothe, H. & Azapagic, A. The carbon footprint of bread. *Int. J.*
23 *Life Cycle Assess.* **16**, 351-365 (2011).
- 24 17. Andersson, K. & Ohlsson, T. Life cycle assessment of bread produced on different scales.
25 *Int. J. LCA* **4**, 25 - 40 (1999).

- 1 18. Paustian, K. *et al.* Climate-smart soils. *Nature* **532**, 49-57 (2016).
- 2 19. Grassini, P. & Cassman, K.G. High yield maize with large net energy yield and small
3 global warming potential. *Proc. Nat. Acad. Sci. USA* **109**, 1074-1079 (2012).
- 4 20. Gan, Y. *et al.* Improving farming practices reduces the carbon footprint of spring wheat
5 production. *Nature Commun.* 5:5012 | DOI: 10.1038/ncomms6012 (2014).
- 6 21. Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature* **528**, 51-58
7 (2015).
- 8 22. Brentrup, F. & Palliere, C. Nitrogen use efficiency as an agro-environmental indicator
9 (www.oecd.org/tad/sustainable-agriculture/44810433.pdf).
- 10 23. Mueller, N.D. *et al.* Closing yield gaps through nutrient and water management. *Nature*
11 **490**, 254-257 (2012).
- 12 24. Jensen, E.S. *et al.* Legumes for mitigation of climate change and the provision of
13 feedstock for biofuels and biorefineries. A review. *Agron. Sustain. Dev.* **32**, 329-364
14 (2012).
- 15 25. Cameron, D.D. Arbuscular mycorrhizal fungi as (agro)ecosystem engineers. *Plant and*
16 *Soil* **333**, 1-5 (2010).
- 17 26. Han, M. *et al.* The genetics of nitrogen use efficiency in crop plants. *Annu. Rev. Genetics*
18 **49**, 269 -289 (2015).
- 19 27. Xu, G., Fan, X. & Miller, A.J. Plant nitrogen assimilation and use efficiency. *Annu. Rev.*
20 *Plant Biol.* **63**, 153-182 (2012).
- 21 28. Long, S.P., Marshall-Colon, A. & Zhu, X-G. Meeting the global food demand of the
22 future by engineering crop photosynthesis and yield potential. *Cell* **161**, 56-66 (2015).
- 23 29. Mosleth, E.F. *et al.* A novel approach to identify genes that determine grain protein
24 deviation in cereals. *Plant Biotech. J.* **13**, 625–635 (2015).

- 1 30. Oldroyd, G.E.D. & Dixon, R. Biotechnological solutions to the nitrogen problem.
2 *Current Opinion in Biotechnology* **26**, 19-24 (2014).
- 3 31. DEFRA. *Green food project bread subgroup report*.
4 (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69572/pb
5 [13797-greenfoodproject-breadsubgroup.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69572/pb)).
- 6 32. Davidson, E.A., Suddick, E., Rice, C.W. & Prokoby, L.S. More food, low pollution (Mo
7 Fo Lo Po): a grand challenge for the 21st century. *J. Environ. Qual.* **44**, 305-311 (2015).
- 8 33. Trudge, C. *Six steps back to the land. Why we need small mixed farms and millions more*
9 *farmers*. (Green Books, Cambridge, England. 2016).
- 10 34. Weidema, B.P. *et al. The ecoinvent database: Overview and methodology, Data quality*
11 *guideline for the ecoinvent database version 3*, www.ecoinvent.org (2013).
- 12 35. Guinée, J.B. *et al. Handbook on life cycle assessment. Operational guide to the ISO*
13 *standards. I: LCA in perspective. Iia: Guide. Iib: Operational annex. III: Scientific*
14 *background*. (Kluwer Academic Publishers ISBN 1-4020-0228-9 Dordrecht. 2002).
- 15 36. Svanes, E., Vold, M. & Hanssen, O.J. Effect of different allocation methods on LCA
16 results of products from wild-caught fish and in the use of such results. *Int. J. Life Cycle*
17 *Assess.* **16**, 512 (2011).
- 18 37. ISO 14040:2006 *Environmental Management – Life Cycle Assessment – Principles and*
19 *Framework*. (BSI, London. 2006).
- 20 38. ISO 14044:2006 *Environmental Management – Life Cycle Assessment – Requirements*
21 *and Guidelines*. (BSI, London. 2006).
- 22 39. Fujihara, S., Sasaki, H., Aoyagi, Y. & Sugahara, T. Nitrogen-to-protein conversion
23 factors for some cereal products in Japan. *J. Food Sci.* **73**, 204-209 (2008).
- 24 40. Bouwman, A.F., Boumans, L.J.M. & Batjes, N.H. Modeling global annual N₂O and NO
25 emissions from fertilized fields. *Global Biochemical Cycles* **16**, 1-9 (2002).

- 1 41. IPCC, Intergovernmental Panel on Climate Change: 2006 IPCC Guidelines for National
2 Greenhouse Gas Inventories. IGES, Hayama, Japan. (2006).
- 3 42. Brentup, F. & Palliere, C. GHG Emissions and energy efficiency in European nitrogen
4 fertiliser production and use. *Proc. International Fertiliser Soc.* **639** (2008).

5

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9

10 **Author contributions**

11 PH and SCLK conceived the study, LG and RB negotiated with the commercial partners, and
12 LG carried out the collection and analysis of the data. All authors were involved in the
13 interpretation of the findings and the writing of the paper.

14

15 **Author Information.**

16 The authors declare no competing financial interests. Correspondence and requests for
17 materials should be addressed to Peter Horton (p.horton@sheffield.ac.uk).

18

19 **Supplementary Information**

20 Pdf files

21 Supplementary Data Figures 1-6 and Supplementary Table 1

22

1 **Figure Legends**

2

3 **Figure 1. The wheat-to-bread supply chain.** A. Map of the supply chain showing
4 cultivation, mill and bakery stages. Sources of energy/ material flow data from two industry
5 partners are also shown. These sources are a large commercial bread maker with multiple
6 production sites across the UK and a wheat farm, producing group 1 and 2 milling wheat at
7 9.5t/ha during the 2014 harvest. B: Supply chain stages and their component processes.

8

9 **Figure 2. Process group environmental impact.** Each coloured bar section represents the
10 environmental impact of process groups at cultivation, mill and bakery stages as shown in
11 Figure 1, expressed as percent of total values. Material and energy input data were assessed
12 alongside six impact categories selected from the CML (2001)³⁵ environmental impact
13 categorisation model produced by the Institute of Environmental Sciences (CML) at Leiden
14 University. AP, acidification potential; GWP, global warming potential; EP, eutrophication
15 potential; FAETP, freshwater aquatic ecotoxicity potential; FSTP, freshwater sediment
16 toxicity; HTP, human toxicity potential.

17

18 **Figure 3. Environmental impact of ammonium nitrate fertiliser in comparison to other**
19 **process groups.** The data for process groups were aggregated to give total impacts for
20 ammonium nitrate (blue), and the cultivation (minus ammonium nitrate) (red), milling
21 (purple), baking (cyan) and storage/transport (green) stages as in Figure 1. The six
22 environmental impact categories are as described in Figure 2.

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