Personal Nitrogen Footprint Tool for the United Kingdom

Carly J. Stevens,*[a] Allison M. Leach,[b] Sarah Dale,[a] James N. Galloway[b]

[a] Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, IK

[b] Environmental Sciences Department, University of Virginia, Charlottesville, Virginia, USA

*to whom correspondence should be addressed. C.Stevens@lancaster.ac.uk

Abstract

The global nitrogen (N) cycle has been transformed by human use of reactive N as a consequence of increased demand for food and energy. Given the considerable impact of humans on the N cycle, it is essential that we raise awareness amongst the public and policy makers as this is the first step in providing individuals and governments the opportunity to reduce their impact on the N cycle and reduce the environmental and health consequences of N pollution. Here we describe an N footprint tool for the UK developed as part of the N-PRINT program. The current per capita N footprint in the UK is 27.1 kg N/capita/yr with food production constituting the largest proportion of the footprint (18.0 kg N/capita/yr). Calculating an N footprint for 1971 (26.0 kg N/capita/yr) demonstrates that per capita N footprints have increased slightly. The average UK footprint is smaller than that found in the USA but is higher than The Netherlands and Germany. Scenario analysis demonstrates that reducing food protein consumption to the levels recommended by the FAO and World Health Organization reduces the overall N footprint by 33%. Consuming a vegetarian diet and consuming only sustainable food both decreased the N footprint by 15% but changes in energy use have a much smaller impact.

Introduction

The global nitrogen (N) cycle is being transformed at a record pace. Between 1860 and 2010 anthropogenic creation of reactive N (Nr) increased more than ten-fold from 15 to 210 Tg N/year[1]. The reasons behind the increases in Nr production are clearly understood; between 1860 and 2010 energy and food production not only increased with the rapidly growing world population, but per capita use also increased. Globally crop and meat production has had to increase to meet the demands of the growing human population. A substantial proportion of grain production is used for animal feed, over half of the grain produced in the US is used as feed crops[2]. In addition, between 1961 and 2007, per capita demand for crop calories and protein also increased steadily, with demand closely related to gross domestic product (GDP)[3]. This has been made possible with the Haber-Bosch process, which has created an essentially endless supply of synthetic fertilizer for food production and is now the major source of Nr to the global terrestrial environment. Energy production by fossil fuel combustion has also increased rapidly with large increases in the developing world (Galloway et al., 2008; Fowler et al., 2013).

Severe inefficiencies in Nr use in agricultural systems have led to a scientific challenge to control the fate of Nr in cropping systems. These systems are under intense pressure to sustain high yields due to the world's limited supply of productive land[4]. Furthermore, without emissions controls, all of the Nr produced during energy production by fossil fuel combustion is lost to the environment. A wide range of environmental problems can be observed as a consequence of increasing Nr in the environment. For example, in the atmosphere Nr adds to particulate matter, smog, stratospheric ozone depletion, and an enhanced greenhouse effect; in terrestrial ecosystems it contributes to biodiversity loss, forest dieback, and soil acidification; and in marine and freshwater ecosystems it contributes to

51   ocean acidification and eutrophication, which are related to biodiversity loss and algal

52   blooms [5]. These impacts are all linked via the N cascade, the transfer of Nr between

53   ecosystems by multiple pathways [6]. Excess Nr also impacts human health. Although Nr

54   availability brings benefits through increased crop production, high levels of food production

55   have led to unbalanced diets with high levels of meat consumption [2]. High levels of Nr in

56   water and air have been linked to human ailments, diseases and allergies [7].

57   In the United Kingdom (UK), changes in the use of Nr through food and energy consumption

58   reflect global patterns. Between 1961 and 2009 supply of the majority of food types

59   increased in the UK. In the case of alcoholic beverages, cereals, starchy roots, and meat,

60   increases in supply between 1961 and 2009 are in excess of one million tonnes. The supply of

61   vegetables increased by more than two million tonnes in this period, milk by over three

62   million tonnes, and fruit by more than four million tonnes (Figure 1). Over a similar time

63   period (1970 to 2012) total combustion of fossil fuels and demand for energy has fallen very

64   slightly in the UK, although current levels are not the lowest during this period. Declines

65   have mostly been seen in the energy use within industry, possibly due to a combination of

66   increased energy use efficiency and declining industry in the UK. There have been

67   substantial increases in energy use within transport (Figure 2) [8].

68   The abundance of Nr in the environment has been increased by human activity more than any

69   other chemical element [9]. Globally humans contribute approximately double the amount of N

70   to the environment that natural processes do [10] whereas for CO_2 emissions, human activities

71   contribute between 5 and 10 % [11]. With this considerable impact of humans on the N cycle, it

72   is essential that we raise awareness amongst the public and policy makers. Raising

73   awareness is the first step in giving individuals and governments the opportunity to reduce

74   their impact on the N cycle and reduce the environmental and health consequences of N

75   pollution. As a step towards this an international team of scientists have been developing a

76 group of tools in the N-PRINT program (www.n-print.org). These tools will ultimately be

77 able to describe losses of Nr associated with consumption patterns of an entity, such as an

78 individual or an institution. Links will then be made to its impact on the environment from

79 individual consumers and collective consumption behaviour together with identifying ways

80 that policy can influence these losses [10].

81 In this paper we focus on the N-Calculator tool, which is an N footprint tool individuals can

82 use to calculate the Nr lost to the environment from the food they eat, the energy they use,

83 and the goods and services they use. An N footprint is defined as the total amount of reactive

84 N released to the environment as a result of an entity's resource consumption. The tool

85 provides an assessment of not only the Nr in food and energy consumed by the individuals,

86 but also the release of Nr through the production of food, energy, goods and services used by

87 individuals. This tool helps consumers connect their consumption patterns to the N cycle.

88 Nitrogen calculators have already been developed for the USA, Netherlands, and Germany;

89 the model is described in detail in Leach et al. [10]. In this paper we present an N footprint tool

90 for the United Kingdom (UK). We also make comparisons with other countries for which we

91 have N footprints available, examine how the N footprint has changed over time in the UK,

92 and present scenarios for N footprints in the UK based on changes in resource use.

93

94 **Methods**

95 The methods for the UK N-Calculator follow those described in Leach et al. [10]. The N

96 footprint is composed of two distinct parts: food and energy.

97 A food N footprint is the sum of the food consumption and food production N footprint. For

98 the UK, the food consumption component was first determined using FAO food supply data

99   and protein content for the UK using the base year 2007 [8]. Food protein supply is multiplied

100   by the N content and and average food waste data for Europe [12] is subtracted. The average

101   rate of denitrification at sewage treatment plants (Anglian Water, personal communication)

102   was applied to the food consumption N footprint. Food production was then addressed by

103   modifying the US virtual N factors (VNF), which describe the average amount of reactive N

104   released to the environment per unit of N consumption [10]. The VNF includes all Nr losses

105   from the system such as fertiliser not incorporated into the plant and crop residues not used as

106   food. For every stage of the food production process six N parameters were considered:

107   Available N, % of previous N available, N waste produced, % N recycled, N recycled, and N

108   loss. Developed for specific food types, the US VNF data were modified only for the final

109   two stages of food production (processing and food waste) with Europe-specific food waste

110   figures (Table 1). The modified US VNF were considered appropriate to use for the UK

111   because food production in the two developed countries is dominated by conventional,

112   industrial processes [13]. Using individual consumption based on answering questions on

113   amount of food portions consumed, values can be translated into a personal food footprint.

114   The UK energy N footprint was determined using a combination of a bottom-up and top-

115   down approach. The bottom up approach is calculated by collecting housing and transport

116   energy consumption data and multiplying it by NO_x emission factors [14-15] for the major types

117   of energy consumption in the UK to give total emissions. Housing energy use included

118   electricity [16], natural gas [17], wood, solar and geothermal [18]. Housing energy use per household

119   was divided by mean number of persons per household [19]. The addition of alternative fuels,

120   such as wood and renewables, is unique from the US N-Calculator. Transport energy use

121   included personal petrol car, diesel car, and motorcycle, public bus and rail [20], and airplane [21].

122   Public transport and airplane use was corrected for average number of passengers per vehicle

123   [21-22]. The final component of the UK energy N footprint was calculated using an

124 environmentally extended input output (EEIO) analysis, a procedure that is widely used for

125 footprint and sustainable consumption analyses [23-25]. This analysis utilises economic input-

126 output tables and sector level emissions to allocate national N emissions to personal

127 consumption patterns in all categories of the footprint: food, housing, transport, goods, and

128 services. Nitrogen emissions calculated from the bottom-up approach described above were

129 subtracted from the findings of the EEIO analysis to avoid double-counting. Using values on

130 individual energy consumption and distances travelled values can be calculated for individual

131 N footprints.

132 An N footprint was compiled for the year 1970 to provide temporal comparison. The year

133 1970 was selected because it was the oldest year for which all necessary data were available.

134 Food consumption and protein content data were taken from FAOSTAT [8]. Food waste and

135 virtual N footprints were unchanged from the 2007 model. The rate of denitrification at

136 sewage treatment plants was assumed to be zero in 1970. Energy consumption data for the

137 UK were taken from DECC [26] incorporating values for the number of UK households [27].

138 Transport data were taken from national datasets [22, 28]. Emission factors for 1970 were taken

139 from the NAEI database [14] and used to calculate percentage change in emission factors. The

140 UK N-calculator was compared to existing calculators in the US, Netherlands, Germany and

141 the US [10].

142 The current UK N-Calculator (2007) was used to test scenarios to see how the average UK N

143 footprint would be affected by changes in consumption patterns. The following scenarios

144 were considered:

1. *Recommended protein*: Protein consumption is reduced to the level recommended by

146   the FAO and World Health Organization (3 kg N/capita/yr), with the dietary

147   composition otherwise remaining the same [29-30].

148   2. *Vegetarian diet*: Meat protein consumption is replaced by vegetable, dairy, and egg

149   protein. Total protein consumption remains the same as current consumption levels.

150   3. *50% food waste*: Food waste is reduced by half. The current diet is used.

151   4. *Sustainable food*: Only food produced sustainably in terms of N is consumed.

152   Sustainable food is defined here as the efficiency possible with currently available

153   technology, as defined by the USEPA Science Advisory Board [31]. The possible N

154   efficiency improvements and emissions avoidance for the US were applied to the UK

155   VNF, assuming that the same efficiency improvements could be achieved in the UK.

156   5. *Advanced WWTP (wastewater treatment plant)*: Advanced sewage treatment with

157   denitrification to remove Nr is expanded from current levels (2%) to 100% of the

158   country's population. Treatment is assumed to denitrify 70% of the reactive N in

159   human waste [32].

160   6. *Renewable energy*: Switch from coal and gas consumption to only renewable energy.

161   7. *Public transit*: Replace 50% of personal car travel with travel by bus and rail.

162   8. *Combination*: Accomplish all analysed scenarios (#1-7).

163

Results

165   The current per capita N footprint in the UK is 27.1 kg N/capita/yr (Table 2). The footprint is

166   dominated by the food production sector (18.0 kg N/capita/yr). The average rate of N

167   consumption is 5.0 kg N/capita/yr, but the 2% rate of denitrification during sewage treatment

168   (Anglian Water, personal communication) reduces the food consumption N footprint to 4.9

169   kg N/capita/yr. The energy sectors contribute the remaining 4.2 kg N/capita/yr.

170

171   The average N footprint for the UK for 1970 is marginally lower than the N footprint in 2007

172   (Table 2). The N footprint for food consumption is slightly lower in 1970 than in 2007, a

173   small difference which masks quite large changes in some components of the British diet

174   (Table 3). In 1970 there was generally more red meat, offal, and eggs consumed per capita

175   whereas in 2007 there was more poultry meat, milk, cheese, cereals and fruit and vegetables

176   consumed. Differences in household energy use represent the category with the largest

177   difference between 1970 and 2007, increasing from 1.3 to 2.0 Kg N per capita (Table 2).

178   There are large increases in electricity and gas use, although this is partially offset by a

179   reduction in the emission factor for electricity (Table 3). Unfortunately information was not

180   available for the emission factor for natural gas in 1970. For transport there is the same

181   footprint in 1970 as 2007 (Table 2) but distance travelled by private car is higher in 2007 than

182   1970. Emission factors are considerably reduced for petrol and lower for diesel. Bus travel

183   has reduced but train travel has increased, although both show reduced emission factors. Air

184   travel is reduced but unfortunately there was insufficient information available to calculate

185   comparable emission factors so the 2007 emission factor was used for the 1970 footprint.

186

187   Comparison between national N footprints for the United States, Netherlands, Germany and

188   UK reveals differences in N released from food consumption, food production, housing and

189   transport (Figure 3). Overall the US has the largest N footprint followed by the UK,

190   Germany and The Netherlands. N losses due to food consumption are similar in the US and

191   UK but lower in The Netherlands and Germany. Energy consumption in housing is highest in

192   the US followed by Germany, with The Netherlands and UK having similar lower values. N

193   losses due to transport are considerably higher in the US than European countries

194   investigated, with the UK and The Netherlands showing the lowest values.

195

196   Food and energy scenarios were tested to reveal how an individual's N footprint could

197   change as a result of changes in consumption patterns. Of the individual scenarios tested,

198   reducing food protein consumption to the recommended level had the biggest impact,

199   reducing the overall N footprint by 33% (Figure 4). Consuming a vegetarian diet and

200   consuming only sustainable food both decreased the N footprint by 15%. The energy

201   scenarios had a smaller impact. Replacing all household fossil fuel use with renewable energy

202   use reduced the footprint by just 4%, and replacing car travel with public transit did not have

203   a measurable impact. A combined scenario that took into account reductions from all

204   scenarios led to a total N footprint reduction of 63%, from 27.1 kg N/cap/yr to 10.0 kg

205   N/cap/yr.

206

207   **Discussion**

208   Footprint tools provide a readily understandable metric of human impact on the natural world

209   and have been used extensively in recent years for carbon emissions, water use, and impact

210   on the environment with ecological footprints. The N footprint tool is a unique tool allowing

211   people to calculate their own person impact on the N cycle. Awareness of the disruption of

212   the global N cycle amongst the public and policy makers is generally poor so this tool

213   provides an essential communication device to demonstrate how changes in diet and lifestyle

214   can reduce individual impacts on the production of Nr. The tool is available on the N-PRINT

215   website (www.n-print.org).

216

217   The relatively small increase of 1.1 kg N in the average N footprint between 1970 and 2007

218   in the UK masks some considerable changes in consumption patterns and emissions between

219   different sources. These changes reflect a broad range of lifestyle changes that have been

220   seen in the UK over the last forty years. Since 1970 the proportion of people in higher

221   education has increased from 621,000 to 2.5 million, less people are getting married,

222   households are smaller, women are having their first child later and life expectancy has

223   increased [33].

224

225   Food is the most significant component of the N footprint. Food contributes to the N footprint

226   through both losses during food N consumption and production. Results show a small

227   increase in the average N footprint from diet, but this result obscures considerable changes in

228   the supply of different food categories. For example, per capita consumption of pigmeat,

229   bovine meat, animal fats and offals have all fallen. A survey of UK residents published in

230   2003 indicated that over a quarter of UK residents considered themselves to be reducing meat

231   consumption due to concern over healthiness, taste, value for money, and ethical concerns [34].

232   A number of studies have reported an association of red meat with cardiovascular disease and

233   cancer. In addition, concerns over the safety of beef related to the bovine spongiform

234   encephalopathy (BSE) outbreak may have reduced the consumption of red meat [35-36]. Egg

235   consumption has also declined, possibly related to the salmonella scare in 1989, growing

236   awareness of diet and awareness of issues concerning bird welfare [37]. This has been replaced

237   by higher consumption of white meat, milk, cheese, cereals, fruit and vegetables and an

238   increase in the total food supply for animal and vegetable products per person per year. In

239   this example we kept the N efficiency in food production constant between 1970 and 2007,

240   although it is likely this provides an underestimate since fertiliser use in tillage crops in

241   England and Wales increased from 84 to 152 kg ha^{-1} between 1970 and 2007 whilst to grass

242   crops it increased and declined again, resulting in little change [38].

243

244   Energy consumption and transport both release N through the combustion of fossil fuels,

245   which releases NO_x emissions. Household energy use makes a comparatively small

246   contribution to the overall N footprint compared to that from food. Electricity and natural gas

247   use increased considerably between 1970 and 2007, which is likely to be at least related to

248 the dramatic rise in the use of consumer electronics in households [39]. Transport shows no

249 change in its footprint, but this conceals large increases in vehicle use. In 1970 48% of

250 households in Great Britain did not have regular use of a car, and in 2008 this was reduced to

251 22% of households. However, this change in car use is offset by massive reductions in

252 emission factors brought about by both improvements in engine design and fitting three-way

253 catalysts to petrol cars [40].

254

255 There is a substantial difference in the N footprints between countries. Food production

256 values were not fully adapted for individual countries due to a shortage of information but in

257 other sectors there are noticeable differences between the US and Europe. The N footprint

258 associated with food consumption is considerably higher in the US than either the

259 Netherlands or Germany. Leach et al. [10] compared the N footprints of the US and

260 Netherlands, reporting that a higher proportion of the footprint came from meat N in the US

261 compared to the Netherlands where the main contributors were dairy, milk and fish. The food

262 consumption footprint in Germany is only marginally higher. In contrast the UK has an N

263 footprint from food consumption almost as high as the US, which is partly accounted for by

264 high meat and dairy consumption. Another factor in this part of the N footprint is the use of

265 advanced sewage treatment with nutrient removal technology. Almost the entire Netherlands

266 is serviced by advanced wastewater treatment meaning that 78% of the food consumption N

267 footprint is removed by advanced wastewater treatment [41]. In the US and the UK advanced

268 sewage treatment with nutrient removal is much less extensive covering 5% of the US [10] and

269 2% of the UK (Anglian Water, personal communication).

270

271 Energy use is also lower in Europe than the US. The largest difference can be seen in the

272 transport sector. On average Americans drive 400 km per week but in the UK this is 164 km

273   per week. The US is the country with the highest dependence on automobiles in urban areas

274   in the world with levels much higher than other countries. This is related to wealth, land use

275   patterns, transport infrastructure priorities and transit provision [42]. Public transport is much

276   more widely used in Europe than the US; emissions from public transport are smaller than

277   from personal vehicles resulting in a much smaller impact on the N footprint. The US also

278   has higher household energy consumption than European countries. Differences between

279   countries in Europe are relatively small, although energy use in housing is higher in the UK

280   than the Netherlands and Germany.

281

282   The footprint scenario analysis in the UK shows the potential for changes in personal

283   consumption patterns on the use and loss of Nr. The food scenarios all had a larger impact

284   than the energy scenarios. Combining all analysed scenarios led to an overall N footprint

285   reduction of 63%. Scaled up to the population of the UK, this could lead to an annual

286   reduction in Nr losses of approximately 1 Tg Nr. However some of the scenarios are easier

287   than others to achieve on a personal level. For example, individuals can generally choose how

288   much food they eat, what types of food they eat, and how they manage their food waste.

289   Consumers do not have control over the treatment level at their local wastewater treatment

290   plant. Some scenarios, such as the consumption of sustainable food and the exclusive use of

291   renewable energy sources, could also be cost-prohibitive. However most of the analysed

292   scenarios are achievable on a personal level and can have a substantial impact on Nr losses,

293   especially when adopted at a large scale.

294

295   **Conclusion**

296   Anthropogenic N use and loss rates are increasing on a global scale and are expected to

297   continue to increase with population growth and shifting dietary patterns. The UK N footprint

298 has only increased slightly since 1970, but the total Nr loss is magnified by population

299 growth. The negative environmental and human health consequences of excess Nr require

300 action to reduce Nr loss to the environment. One way to achieve these reductions is through

301 changes in personal consumption patterns. The UK N-Calculator informs consumers about

302 how N is released to the environment and how their personal choices impact those Nr losses.

303 Individuals can choose from a variety of changes in personal consumption patterns to reduce

304 their impact, with significant reductions possible. These personal consumption changes,

305 combined with increased efficiency at the production level, will reduce the loss of Nr and its

306 detrimental consequences.

307

310

311 **References**

312 1.   D. Fowler, M. Coyle, U. Skiba, M. A. Sutton, J. N. Cape, S. Reis, L. J. Sheppard, A.

313   Jenkins, B. Grizzetti, J. N. Galloway, P. Vitousek, A. M. Leach, A. F. Bouwman, K.

314   Butterbach-Bahl, F. Dentener, D. Stevenson, M. Amann and M. Voss, *Philosophical*

315   *Transactions of The Royal Society B*, 2013, 368, 20130164.

316 2.   R. W. Howarth, E. W. Boyer, W. J. Pabich and J. N. Galloway, *Ambio*, 2002, 31, 88-

317   96.

318 3.   D. Tilman, C. Blazer, J. Hill and B. L. Befort, *Proceedings of the National Academy*

319   *of Sciences*, 2011, 108, 20260–20264.

320 4.   K. G. Cassman, A. Dobermann and D. T. Walters, *Ambio*, 2002, 31.

321 5.   M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H.

322   Van Grinsven and B. Grizzetti, eds., *The European Nitrogen Assessment: Sources,*

323   *effects and policy perspectives*, Cambridge University Press, Cambridge, 2011.

324 6.   J. N. Galloway, J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B.

325   Cowling and B. J. Cosby, *BioScience*, 2003, 53, 341-356.

326 7.   A. R. Townsend, R. W. Howarth, F. Bazzaz, M. S. Booth, C. C. Cleveland, S. K.

327   Collinge, A. P. Dobson, P. R. Epstein, E. A. Holland, D. R. Keeney, M. A. Mallin, C.

328   A. Rogers, P. Wayne and A. H. Wolfe, *Frontiers in Ecology and Environment*, 2003,

329   1, 240-246.

330 8.   Food and Agriculture Organization of the United Nations, FAO STAT,

331   http://faostat.fao.org/site/345/default.aspx, Accessed September 2013.

332 9.   J. W. Erisman, A. Bleeker, A. Hensen and A. Vermeulen, *Atmos. Environ.*, 2008, 42,

333   3209-3217.

334 10.   A. M. Leach, J. N. Galloway, A. Bleeker, J. W. Erisman, R. Kohn and J. Kitzes,

335   *Environmental Development*, 2012, 1, 40-66.

336 11.   C. Le Quéré, *Environmental Sustainability*, 2010, 2, 219-224.

337 12.   J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk and A. Meybeck, *Global*

338   *food losses and food waste*, FAO, Rome, 2011.

339 13.   The World Bank, Indicators, http://data.worldbank.org/indicator, Accessed November

340   2013.

341 14.   National Atmospheric Emissions Inventory, http://naei.defra.gov.uk/data/ef-all.

342 15.   EMEP, *EMEP/EEA air pollutant emission inventory guidebook 2013* European

343   Environment Agency, Copenhagen, 2013.

344   16.   Department of Energy and Climate Change, Sub-national gas consumption data

345   http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/regional/gas/gas.aspx,

346   Accessed August 2013.

347   17.   Department of Energy and Climate Change, Sub-national energy consumption,

348   https://www.gov.uk/government/collections/sub-national-energy-consumption,

349   Accessed August 2013.

350   18.   Department of Energy and Climate Change, Digest of UK energy statistics (DUKES),

351   https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes,

352   Accessed August 2013.

353   19.   Department for Communities and Local Government, General Lifestyle Survey,

354   http://www.esds.ac.uk/findingData/ghs.asp, Accessed August 2013.

355   20.   Department for Transport, Rail passenger numbers and crowding on weekdays in

356   major cities in England and Wales: 2011,

357   https://www.gov.uk/government/publications/rail-passenger-numbers-and-crowding-

358   on-weekdays-in-major-cities-in-england-and-wales-2011, Accessed August 2013.

359   21.   Civil Aviation Authority, UK Airline Statistics: 2011 - annual,

360   http://www.caa.co.uk/default.aspx?catid=80&pagetype=88&sglid=1&fld=2011Annua

361   l, Accessed August 2013.

362   22.   Department for Transport, *Transport Statistics Great Britain 2011*, Department for

363   Transport, London, 2011.

364   23.   K. B. Bicknell, R. J. Ball, R. Cullen and H. R. Bigsby, *Ecological Economics*, 1997,

365   27, 149-160.

366   24.   R. E. Miller and P. D. Blair, *Input–Output Analysis: Foundations and extensions*,

367   Cambridge University Press, Cambridge, UK, Second edn., 2009.

368   25.   T. Wiedmann, J. Minx, J. Barrett and M. Wackernage, *Ecological Economics*, 2006,

369   56, 28-48.

370   26.   Department for Transport, National travel survey statistics,

371   http://www.dft.gov.uk/statistics/series/national-travel-survey/, Accessed August 2013.

372   27.   M. T. Programme, *BNXS25: UK Household and Population Figures 1970 - 2020*,

373   Defra, London, 2007.

374   28.   Office for National Statistics, *Social Trends No. 38*, National Statistics, Cardiff, 2006.

375   29.   Institute of Medicine, *Dietary reference intakes for energy, carbohydrate, fiber, fat,*

376   *fatty acids, cholesterol, protein, and amino acids (macronutrients).* Institute of

377   Medicine of The National Academies, Washington D.C., 2005.

378   30.   World Health Organization, Food and Agriculture Organization of the United Nations

379   and United Nations University, *Protein and amino acid requirements in human*

380   *nutrition: Report of a joint FAO/WHO/UNU expert consultation* World Health

381   Organization, Geneva, 2007.

382   31.   EPA Science Advisory Board, *Reactive nitrogen in the United States: An analysis of*

383   *inputs, flows, consequences and management options.*, Report EPA-SAB-11-013,

384   U.S. Environmental Protection Agency, Washington D.C., 2011.

385   32.   L. Metcalf, H. P. Eddy and G. Tchobanoglous, *Wastewater engineering – Treatment*

386   *and reuse* McGraw-Hill, New York, Fourth edn., 2002.

387   33.   Office for National Statistics, *Social Trends No. 40*, National Statistics, Cardiff, 2010.

388   34.   N. J. Richardson, N. A. Shepherd and N. A. Elliman, *Appetite*, 1993, 21, 41-51.

389   35.   A. J. McAfee, E. M. McSorley, G. J. Cuskelly, B. W. Moss, J. M. W. Wallace, M. P.

390   Bonham and A. M. Fearon, *Meat Science*, 2010, 84, 1-13.

391   36.   W. Verbeke, L. J. Frewer, J. Scholderer and H. F. De Brabander, *Analytica Chimica*

392   *Acta*, 2007, 586, 2-7.

393   37.   A. Fearne and D. Lavelle, *British Food Journal*, 1996, 98, 7-12.

394   38.   Defra, *The British survey of fertiliser practice*, Defra, London, 2008.

395   39.   T. Crosbie, *Energy Policy*, 2008, 36, 2191-2199.

396   40.   Air Quality Expert Group, *Nitrogen dioxide in the United Kingdom*, Defra, London,

397   2004.

398   41.   U. van Waterschappen, *Clean waste water: National comparison of the regional*

399   *water authorities with respect to their water quality management (in Dutch)*, 2006.

400   42.   J. R. Kenworthy and F. B. Laube, *Environmental Impact Assessment Reviews*, 1996,

401   16, 279-308.

402   43.   Department of Energy and Climate Change, *Energy consumption in the UK (2013)*,

403   Department of Energy and Climate Change, London, 2013.

404

405   **Tables**

406

407   **Table 1.** Comparison of virtual N factors for the United States and the United Kingdom, by food type.

Food type	United States virtual N factor	United Kingdom virtual N factor
Poultry	3.2	3.2
Pigmeat	4.4	4.4
Beef	7.9	7.9
Milk	4.3	3.9
Fish	4.1	2.9
Cereals	1.4	1.3
Pulses	0.5	0.5
Starchy roots	1.5	1.1
Vegetables	9.6	8.2

408

409

410

411   **Table 2.** Nitrogen footprint for the UK in 1970 and 2007.

| | N footprint (kg N) | |
	1970	2007
Food consumption	4.6	4.9
Food production	17.9	18.0
Housing	1.3	2.0
Transport	1.1	1.1
Goods and Services	1.1	1.1
Total	**26.0**	**27.1**

412

413

414

415

416

417   **Table 3.** Information used in calculating the national average UK footprint for food consumption,

418   energy use and transport in the UK in 1970 and 2007.

Product	1970		2007	
Food	Food supply (kg capita^{-1} year^{-1})	Protein supply (g capita^{-1} day^{-1})	Food supply (kg capita^{-1} year^{-1})	Protein supply (g capita^{-1} day^{-1})
Animal products				
Poultry meat	10.5	4.2	32.2	13.0
Pigmeat	27.5	7.6	26.2	7.2
Bovine meat	24.1	8.5	19.8	7.1
Milk	231.6	19.0	238.2	12.3
Cheese	5.3	3.6	10.3	7.0
Eggs	15.3	4.8	10.3	3.2
Fish and Seafood	20.9	5.2	21.0	6.0
Animal fats	17.4	0.3	6.3	0.1
Offals	4.3	2.0	2.6	1.2
Mutton and goat meat	0.6	0.4	0.8	0.8
Other meat	9.8	3.3	5.2	1.8
Vegetable products				
Stimulants	7.8	1.	8.5	1.7
Cereals	89.6	20.7	108.6	27.2
Rice	1.2	0.3	6.1	1.2
Fruits	61.2	0.8	125.2	1.5
Pulses	3.7	2.3	2.9	1.8
Starchy roots	104.9	4.6	104.5	4.3
Vegetables	75.5	2.9	89.4	3.1
Nuts	0.8	0.2	2.4	0.4
Alcoholic beverages	107.4	1.4	98.2	1.1
Oilcrops	2.8	0.8	3.7	1.5
Spices	0.2	0.1	1.0	0.3
Sugar and sweeteners	49.3	0	37.5	0
Vegetable oils	10.9	0	1.10	0
Energy use	**Energy supply (units household^{-1} month^{-1})**	**Emission factor (Nr unit^{-1})**	**Energy supply (units household^{-1} month^{-1})**	**Emission factor (Nr unit^{-1})**
Electricity (kwh)	156	0.001447	363	0.000107
Natural Gas (m^3)	35	0.001855*	98	0.001855
Land Transport	**Distance travelled (km person^{-1} week^{-1})**	**Emission factor (Nr km^{-1})**	**Distance travelled (km person^{-1} week^{-1})**	**Emission factor (Nr km^{-1})**
Private car	108	0.002913 (petrol)	164	0.000049 (petrol)

		0.000309 (diesel)		0.000125 (diesel)
Bus	21	0.000339	11	0.000006
Rail	12	0.000473	16	0.000005
Motorcycle	1	0.000245	1	0.000006
Air transport	**Time travelling (hours person^{-1} year^{-1})**	**Emission factor (Nr km^{-1})**	**Time travelling (hours person^{-1} year^{-1})**	**Emission factor (Nr km^{-1})**
Aeroplane	0.02	0.060565*	0.2	0.060565

419   *No comparable data available for 1970 so 2007 data were used.

420

421   **Figures**
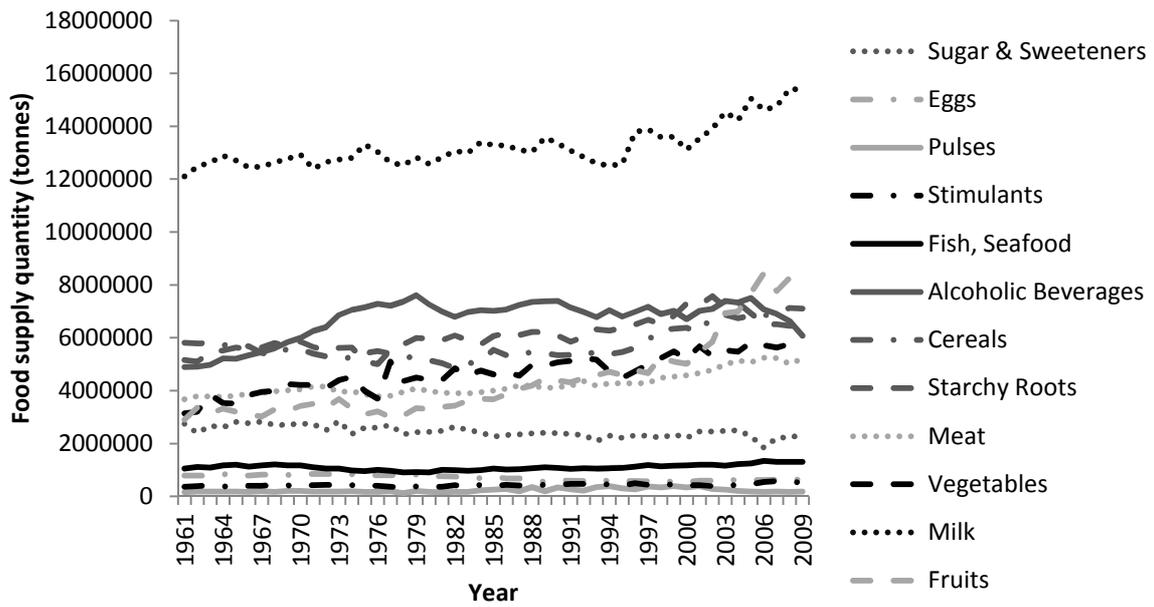
422

423

424   **Figure 1.** Food supply quantity (tonnes) for major food groups between 1961 and 2009 in the UK.

425   Data is taken from FAO [8].

426

427

428
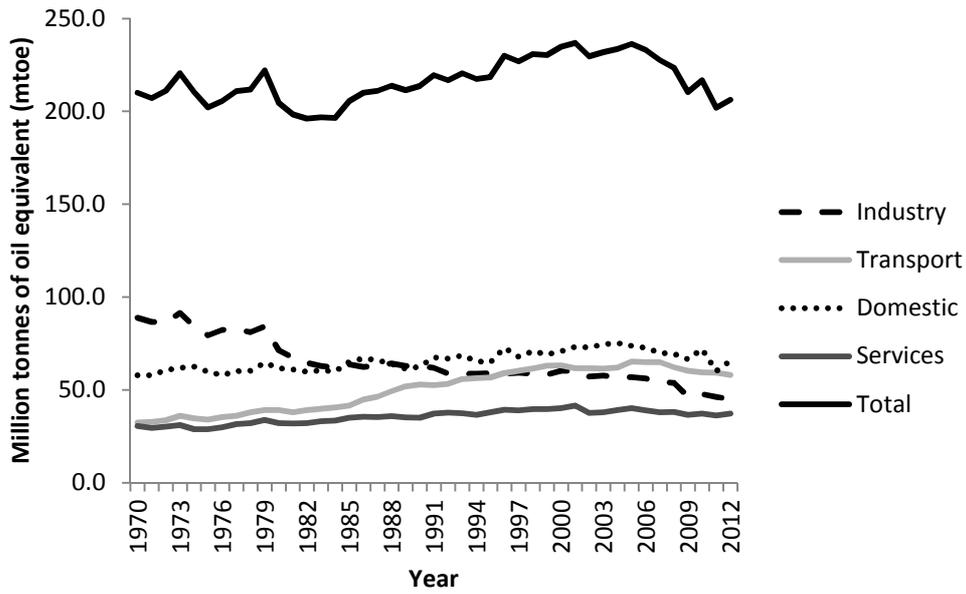
Figure 2. Energy consumption (Million tonnes of oil equivalent) between 1970 and 2012 in the UK.

Data is taken from the UK Department of Energy and Climate Change statistics [43].

431

432
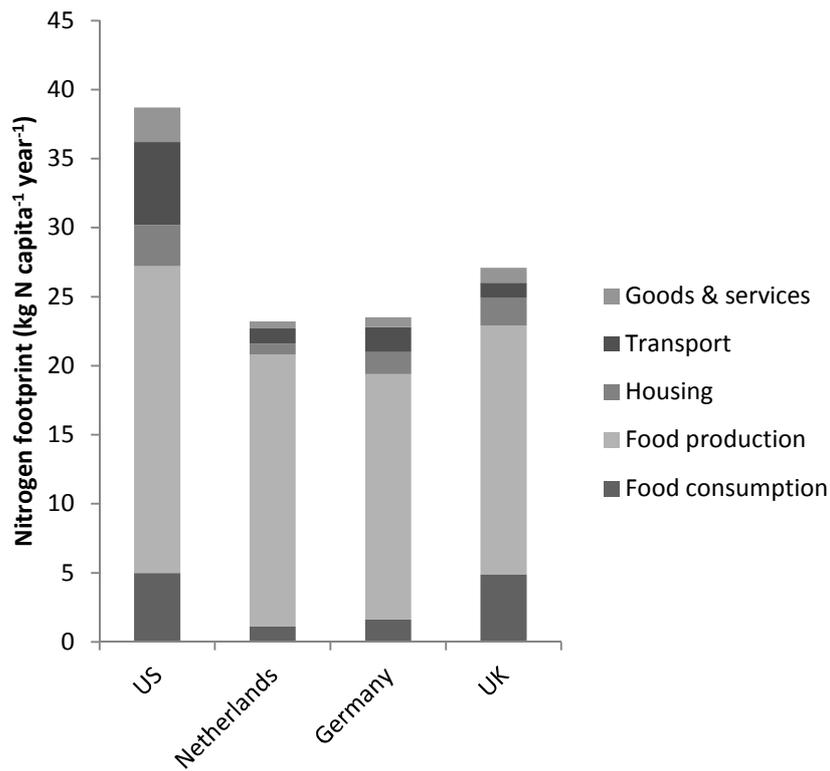
433

434 **Figure 3.** Nitrogen footprints (kg N/capita/yr) for the US, Netherlands, Germany and UK broken

435 down into food consumption, food production, housing, transport and goods and services.

436

437

438

439
440
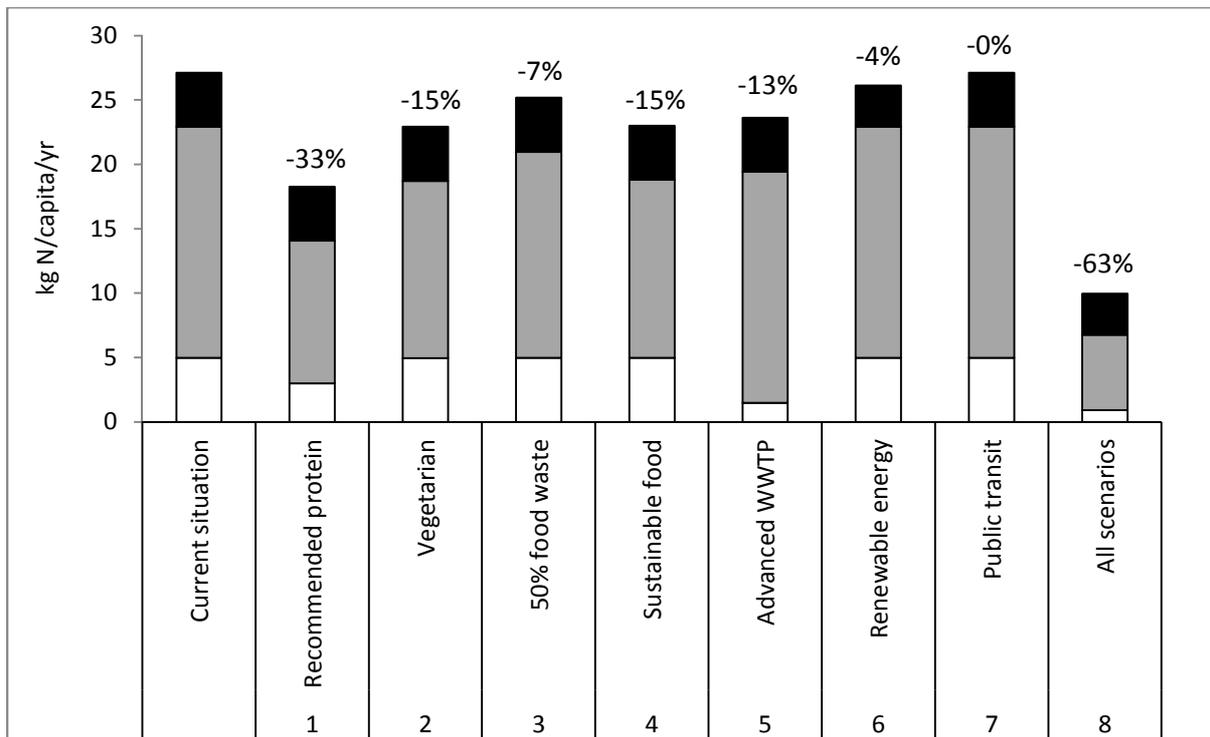
Figure 4. Impact of changes in personal consumption patterns on the N footprint in the United

Kingdom. White bars represent food N consumed, grey bars represent food virtual N, and black bars

represent energy N (i.e., from housing, transport, and goods & services). The percentage above each

bar shows the percent reduction for each scenario relative to the current average UK N footprint. The

scenarios analysed are: 1) scale protein consumption down to the recommended level; 2) consume a

vegetarian diet; 3) reduce food waste by half; 4) consume food produced with best management

practices; 5) treat human waste at an advanced wastewater treatment plant (WWTP) with

denitrification; 6) use only renewable energy sources for household energy; 7) use only public transit

for transport; and 8) combine scenarios 1 through 7.