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## **Analyzing consumer-related nitrogen flows: A case study on food and material use in Austria**

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# 1 Analyzing consumer-related nitrogen flows: A case study on food and 2 material use in Austria

## 3 Abstract

4 Nitrogen budgets cover pools and flows of nitrogen (N) contained in human-made goods and  
5 compounds, which may potentially affect the global nitrogen cycle and in consequence the human  
6 environment. Acknowledging the importance of food and other agricultural products, this paper  
7 additionally investigates frequently neglected flows of N related to consumers and estimates their  
8 magnitude, using Austria in 2010 as an example. Specifically, N in non-food industrial products  
9 (synthetic & natural polymers, wood & paper products, waste), and N related to pets, gardens, and  
10 energy use is considered. Over the last five decades, both food and material consumption have  
11 increased distinctly. While food supply accounts for 52% of total directly consumer-related nitrogen  
12 inflows covered in this study ( $66\,000\text{ t N a}^{-1}$ ), also material products account for a considerable share  
13 of 28% ( $36\,000\text{ t N a}^{-1}$ ). N application in gardens (12%) and N in pet food (7%) do also play a role.  
14 Quantified outflows are human excretion (54%), food waste (13%), garden waste (16%), material  
15 waste (7%) and waste from pets (10%). The detected balance surplus of  $34\,000\text{ t N a}^{-1}$ , corresponding  
16 to 27% of total inflows, points to some accumulation of N in the form of durable consumer goods and  
17 to potentially missing flows. The analysis focusses on the apparent knowledge gaps. Especially flows  
18 involving material products are poorly understood and would require better understanding of  
19 nitrogen contents of products and of waste. This indicates that improvements may be possible by  
20 providing more complete nitrogen budgets in the future that cover all environmental pools.

21

22 **Keywords:** nitrogen budget, consumers, food, material products

## 23        **1. Introduction**

24        Human influence has notably altered the complex natural nitrogen (N) cycle. Over the course of the  
25        last century, the widespread use of Haber-Bosch synthesis significantly increased the amount of fixed  
26        nitrogen available for human use, mainly as fertilizer for food production. However, nitrogen is not  
27        only necessary and beneficial, but also has problematic effects on the environment and human  
28        health (see e.g. Erisman et al. (2013) and van Grinsven et al. (2013) for recent overviews).

29        Nitrogen budgets are tools to quantify and trace both natural and human-induced flows of nitrogen  
30        through a variety of systems, e.g. on global, regional or national scope, for economic sectors, single  
31        farms, households or watersheds (Leip et al. 2011b; UN ECE 2013). Anthropogenic flows are to a  
32        large extent connected to agricultural production and trade of food and feed, and fuel combustion.  
33        These human-induced flows have been estimated to be in the same order of magnitude as natural  
34        flows with the prospect of further increase. E.g., Galloway et al. (2004) assume that global  
35        anthropogenic N creation will be increasing from 156 Tg N a<sup>-1</sup> in the early 1990s to 267 Tg N a<sup>-1</sup> in  
36        2050, while total natural creation is to decrease from 233 Tg N a<sup>-1</sup> to 224 Tg N a<sup>-1</sup> in the same period.  
37        Consequently, many existing national nitrogen budgets focus on these agricultural and energy-  
38        related aspects, e.g. van Egmond et al. (2002) for Europe, Olsthoorn and Fong (1998) for the  
39        Netherlands, Howarth et al. (2002) for the USA. More recent work includes Leip et al. (2011a) and  
40        Lassaletta et al. (2014), or Saikku et al. (2007) with a focus on energy. Ways to reduce the excess  
41        release of N compounds to the environment have been discussed extensively and include technical  
42        measures and adapted agricultural practices for a more nitrogen-efficient agricultural production  
43        (Spiertz 2010; Sutton et al. 2011; van Egmond et al. 2002). On the consumption side, many authors  
44        suggest shifts in diets (i.e., a reduction of animal-based foods) as well as the substantial reduction of  
45        food waste, especially in the developed world (Smil 2002; van Egmond et al. 2002). While considered  
46        to address nitrogen pollution, these measures would also be beneficial to other environmentally  
47        relevant issues, such as energy consumption, land use or greenhouse gas emissions (Stehfest et al.  
48        2013).

49 However, there are indications that apart from food and energy related flows, other N flows might  
50 also be relevant (Gu et al. 2012, 2013; Leip et al. 2011a). According to Leip et al. (2011a), more than  
51 50% of the (reactive) N that is available for consumers serves other purposes than human nutrition,  
52 mostly in the form of non-food industrial products, but also forest products and pet food. These  
53 aspects have largely been neglected in national nitrogen budgets so far, mainly due to the lack of  
54 robust and consistent data. In addition, it has been argued that these flows are small in comparison  
55 and remain within the margins of uncertainty. The respective N is mostly incorporated in products  
56 and can thus be considered less critical with regard to environmental impacts and societal costs.  
57 While it is true that the N is bound in these products during most of their product lifetime and  
58 accumulates in human settlements, it may still become environmentally relevant when the products  
59 are disposed of (Houlton et al. 2013). The fate of this industrial N, however, remains unclear and  
60 poorly investigated (Galloway et al. 2008).

61 In a comprehensive study of carbon, nitrogen and phosphorus fluxes related to households, Fissore  
62 et al. (2011) did not only investigate transportation, landscape management, human diet and home  
63 energy use, but also included the less commonly used aspects of pet diet as well as detergents, paper  
64 and plastics. For the latter two, however, only carbon contents were assessed. Olsthoorn and Fong  
65 (1998) mention N flows in raw materials for the production of plastics, nylon and other synthetic  
66 materials, but do not discuss that further. They simply state the accumulation of N in durable, mostly  
67 synthetic, products and assess statistical errors as a balancing item in their national nitrogen balance.

68 While food- and energy-related N flows have thus been analyzed thoroughly, there is a clear lack of  
69 knowledge concerning other anthropogenic N flows, especially with regard to consumers. Demand  
70 from consumers is the central driving force behind all production activities. Consumption choices,  
71 consumer behavior and lifestyle determine not only N flows, but all kinds of material throughput  
72 through the anthroposphere (Brunner and Rechberger 2004; Fissore et al. 2011). Only when all  
73 potentially relevant flows of N have been quantified in a consistent way, a focus on certain aspects  
74 (with regard to environmental/consumer policy) can be justified (Brunner and Rechberger 2004).

75 Against this background, we aim to systematically identify relevant N flows caused and influenced by  
76 consumers in order to trace pathways of N in a more complete way. Based on the principles of  
77 substance flow analysis, we provide quantitative estimates on the magnitude of these flows, using  
78 Austria as an example. Ultimately, this can serve to inform policy decisions and provide a better  
79 knowledge base on whether the current focus on food and agriculture is justified, or whether an  
80 extended perspective is needed (Leip et al. 2011a).

## 81 **2. Materials and Methods**

### 82 **2.1. Boundaries & theoretical background**

83 The geographic boundaries of the system under analysis are the national borders of Austria, with  
84 2010 as the principal year of analysis. For food-related flows the available data also allowed for an  
85 analysis of historic flows back until the 1960's. For material flows, an estimation of the past can be  
86 given based on available timelines from material flow accounting in Austria (Petrovic 2014).

87 In contrast to life cycle or footprint analysis, where all flows along the entire lifetime of a product or  
88 good are considered, in this analysis only the nitrogen that is directly contained in the respective  
89 item is covered. This is among others due to the broad scope of the study. However, it is of relevance  
90 to compare the results with the total impacts related to a product as given for instance by nitrogen  
91 footprints (e.g. Pierer et al. 2014).

92 Commonly with nitrogen budgets, the system under analysis is separated into different  
93 compartments or pools. For national nitrogen budgets (NNB), the UN ECE (2013) recommends to  
94 distinguish eight pools: energy and fuels; material and products in industry; humans and settlements;  
95 agriculture; forest and semi-natural vegetation including soils; waste; atmosphere; hydrosphere.  
96 Instead of providing such a "traditional" complete nitrogen budget (Leip et al. 2011b; UN ECE 2013),  
97 we zoom in and focus on the consumer part, which largely corresponds to the pool "humans and  
98 settlements". This includes first of all food (diets & food waste) and material products available for

99 consumption that accumulate in the consumer sphere or are disposed of (synthetic polymers for  
100 product use, detergents, textiles, wearing apparel & leather, wood & paper products, tobacco).  
101 Furthermore, nitrogen flows related to animals not covered in agricultural statistics are also included  
102 (i.e. “standard” pets such as cats, dogs, small mammals etc., but also non-agricultural pleasure riding  
103 horses). Finally, as an integral part of human settlements and in accordance with UN ECE (2013),  
104 private gardens and public green areas are also considered in this study. In all these cases,  
105 consumption patterns are the central driving forces for the surrounding activities. Thus it proved  
106 useful to extend the analysis towards energy and fuels in order to cover the full range of nitrogen  
107 related to consumers (even as, being covered by energy statistics, this aspect is considered  
108 separately by UN ECE 2013).

109 Nitrogen flows (in particular the release to air, soil and water) related directly to agricultural or  
110 industrial production of goods and services, atmospheric deposition etc. are not included in this  
111 study. Furthermore, we do not trace pathways of N flows outside the core consumer sphere, i.e. in  
112 this analysis the flows end at the stage of waste management, the hydrosphere, or the atmosphere.  
113 In the context of a complete national nitrogen budget, these upstream flows would be covered by  
114 the respective pools (i.e., agriculture, material and products in industry, waste management etc.).  
115 The consumption of services might also cause some N flows, mainly related to energy use. However,  
116 this aspect cannot be separated conceptually, and is implicitly included in household energy use.

117 We consider annual flows that account for more than 100 g N per inhabitant (thus about 850 t N for  
118 Austria in total) as relevant for a NNB. For this quantification, we also scrutinized and accounted for  
119 smaller flows.

120 The procedure applied is inspired by material flow analysis (Brunner and Rechberger 2004; Uihlein et  
121 al. 2006): First, we qualitatively identified products and processes that contain nitrogen and might be  
122 relevant, paying particular attention to non-food related flows. In a next step, we estimated mass  
123 flows and nitrogen concentrations. Finally, we derived N flows by combining the amount of goods

124 and nitrogen contents, which allowed us to identify the most relevant flows. This was done in an  
125 iterative process, i.e. some flows that were included at first were then removed because of  
126 insignificance, such as nitrate in drinking water, pharmaceuticals, metals and ceramic products.  
127 Others that did not seem relevant at first sight were included. This particularly applies to wood and  
128 paper products, which contain N only in very small percentages, but become relevant due to the  
129 large amounts of products consumed. Ideally in this system, inflows correspond to outflows plus  
130 possible changes in stocks. While balance differences (i.e., differences between inflows and outflows)  
131 of 10% are considered commonly acceptable and insignificant for the conclusions (Brunner and  
132 Rechberger 2004), larger differences might indicate missing flows or stock changes.

## 133 **2.2. Data basis & determination of N flows**

134 To determine the N flows, primarily appropriate statistics as well as scientific literature was used.  
135 Sometimes these sources had to be complemented with assumptions. Table A1 of the appendix  
136 provides an overview on the data sources, and Table A2 shows the N contents used.

137 For food products, quantities of food as reported by Statistics Austria and FAO (Statistik Austria  
138 2012b; FAO 2014a, 2014b, 2014c) are multiplied with total N contents (based on Souci et al. 2008  
139 and other N budgets such as Heldstab et al. 2010). All plant oils, as well as sugars and sweeteners are  
140 excluded from the analysis, as they usually do not contain any protein and only negligible amounts of  
141 non-protein N. Not all N available as food is actually consumed by humans, as significant amounts of  
142 food are wasted. The amount of food waste was determined from Austrian waste statistics  
143 (Umweltbundesamt 2012). While this contains a separately declared waste fraction called “food  
144 waste”, also the fraction “biogenic waste” has been assigned to food waste. By contrast, green waste  
145 has been included in “green waste and garden waste”. Furthermore, it has been estimated that an  
146 additional 1.5 million tonnes of material is potentially available for private composting  
147 (Umweltbundesamt 2012). This material consists of biodegradable kitchen waste, plant residues and  
148 biogenic waste from private gardens. As no indication on its composition is given, 50% have been

149 assigned to green waste, and 50% to food waste. To determine N flows for all food-related waste, the  
150 average N content of all food products supplied in 2010 was used (0.84%).

151 Assuming that adults do not accumulate significant amounts of N in their body, most of the N that is  
152 consumed as food needs to be excreted as well. This is either excrements going to the sewage  
153 system or directly to the hydrosphere for households that are not connected to the sewage system  
154 (about 6.1% of all households in Austria, BMLFUW 2012). The total incoming nitrogen load to  
155 municipal sewage treatment plants is reported regularly (BMLFUW 2012). Sutton et al. (2000) also  
156 quantified the amount of N released due to sweating and breathing in the form of  $\text{NH}_3$ , which is  
157 specifically taken into consideration here. Population dynamics, i.e. children who still accumulate  
158 some N in their body mass, as well as the net change in population based on births, deaths and  
159 migration are not included in the analysis as these are natural processes not directly connected to  
160 consumption patterns, and are negligible in their N flows.

161 Pet food and pet waste is determined based on estimations on the number of pets in Austria  
162 (FEDIAF 2010), and protein requirements as given in feeding recommendations (Table A1). There is  
163 no specific information available on the extent to which feeding recommendations are followed.  
164 Overfeeding of pets as well as wastage of pet food might occur, but these aspects are taken into  
165 account via the uncertainty assessment. Animals considered are dogs, cats, ornamental birds,  
166 aquarium fish, small mammals, and pleasure riding horses. As no data on pet excretion is available,  
167 pet excretion and waste was set equal to inflows in the form of pet food, assuming that no significant  
168 accumulation of N occurs in the pets' bodies.

169 Egle et al. (2014) estimate that in Austria about 1-3% of total mineral fertilizer use is dedicated to  
170 private gardens and public green spaces, while the rest is consumed by agriculture. They also assume  
171 that 20% of the available compost is applied as fertilizer in gardens. Average production of compost  
172 amounts to roughly 700 000 t, and total N contents of compost range from 0.6 to 2.3% dry matter  
173 (BMLFUW 2010). The industrial production of compost and emissions of ammonia and nitrous oxides



174 that might occur during the production process (Martínez-Blanco et al. 2010) take place in the sector  
175 waste management and therefore are outside the boundaries of this study. Besides these  
176 professionally produced and statistically covered amounts of compost, large amounts of garden  
177 waste and green waste are used for home composting. As mentioned above, a potential of roughly  
178 1.5 million tonnes of such material for home composting has been estimated for 2010  
179 (Umweltbundesamt 2012). In contrast to the industrial production of compost, home composting is a  
180 conceptual part of the consumer sphere. Consequently, the material available for home composting  
181 is included as outflow on the one hand, and as inflow in the form of compost on the other hand. N  
182 losses in terms of ammonia and nitrous oxide emissions during the home composting process are  
183 accounted for (Colón et al. 2010).

184 Data on N embedded in non-food material products is particularly scarce. For textiles & leather  
185 products, wood and tobacco, the assessment is based on production and foreign trade statistics (FAO  
186 2014a, 2014b, 2014c; Statistik Austria 2012a) and approximated N contents of the respective  
187 products (Table A2). Consumption of paper was determined based on industry reports (Austropapier  
188 2013), as the production of paper from recycled material could not be reliably estimated with  
189 production and foreign trade statistics. With regard to synthetic polymers for product use, it is very  
190 challenging to identify relevant products and determine specific N contents due to the broad range  
191 of products composed of many different materials. Consequently, N flows had to be estimated based  
192 on industry market reports of the basic substances polyamide, polyurethane and melamine in  
193 Europe, broken down into the share for Austria (Table A3).

194 Material waste can be approximated by utilizing waste statistics such as those included in the federal  
195 waste management plan (Umweltbundesamt 2012), although determination of N contents remains  
196 problematic, particularly for aggregated waste fractions such as residual or bulky waste. As an  
197 alternative approximation, Gu et al. (2013) estimate that roughly 25% of yearly inflows of industrial  
198 products accumulate in settlements (i.e. consumer durables that are used for more than one year).

199 With regard to energy, only the outputs, i.e. the emissions of NO<sub>x</sub> and N<sub>2</sub>O are considered. These are  
200 derived by applying average emission factors to the total energy use by households. In combustion  
201 processes, mainly two forms of NO<sub>x</sub> are created: “new” reactive N from the fixation of atmospheric  
202 N<sub>2</sub> in the combustion air, and mobilization of existing reactive N contained in the fuels (Galloway et  
203 al. 2004; Moomaw 2002). Most of the fuel nitrogen, however, is converted to unreactive N<sub>2</sub> (Saikku  
204 et al. 2007). This explains why it is frequently assumed that all NO<sub>x</sub> emissions from combustion stem  
205 from fixation of atmospheric N<sub>2</sub> only, rather than from the fuels per se (van Egmond et al. 2002). Due  
206 to these complex interactions and the role of unreactive N<sub>2</sub>, it is impossible to establish a balance of  
207 inputs and outputs based on reactive N only, and no additional knowledge could be gained by  
208 including N<sub>2</sub> in the system. As a consequence, the flow of N emissions due to energy use is treated  
209 separately and outside the balance of the other flows.

### 210 **2.3. Uncertainty assessment**

211 Due to the lack of established and consistent data sources and the range of necessary assumptions,  
212 the uncertainties related to the presented nitrogen flows are generally high. Where possible, we  
213 used different calculation approaches for the same flow to compare and validate the results (e.g. for  
214 food supply and wood & paper products, as described above). Furthermore, most in- and outflows  
215 could be determined independently from each other, with the exception of pets, where excretion  
216 was set equal to food supply. This procedure allows largely independent validation of the results.

217 However, uncertainty assessment is needed in order to estimate the range of variation of the flows.  
218 As elaborate stochastic modelling and statistical analysis is not applicable to the available data,  
219 uncertainty levels are being used to allow at least indicative quantification. In analogy to Hedbrant  
220 and Sörme (2001), we assigned the data to a set of four uncertainty levels and the respective  
221 uncertainty factors (UF, see Table 1)<sup>1</sup>. Whereas this approach originally has been developed in the  
222 context of urban heavy-metal metabolism, it was also used for Austrian national nutrient balances,

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<sup>1</sup> These factors are also compatible with the ratings and typical error ranges from the EMEP/EEA air pollutant emission inventory guidebook 2013 (European Environment Agency 2013).

223 e.g. by Obernosterer and Reiner (2003) or Egle et al. (2014). Based on the likely value for a nitrogen  
224 flow, the uncertainty interval can be derived by both multiplying and dividing by the respective  
225 uncertainty factor.

226 **Table 1: Levels of uncertainty** (based on Hedbrant and Sörme 2001, Egle et al. 2014)

Level	Uncertainty Factor (UF)	Application
1	1.1	current official statistics, measurement data, data from appropriate literature
2	1.33	expert estimates, outdated official statistics, unofficial statistics, presentations, industry reports
3	2.0	assumptions for which neither official statistics nor expert estimates were available often based on based on on-line data sources or publications without accurate literature reference
4	4.0	an estimate based on a calculation derived from assumptions only

227

### 228 **3. Results and Discussion**

229 The main directly consumer-related N flows that have been quantified in this study for Austria in  
230 2010 are summarized in Table 2. Total inflows of N to the consumer sphere amount to 126 713 t N  
231 (with uncertainty estimates ranging from 99 000 to 171 000 t N), and consist of food supply (52%),  
232 material products (28%), N application in gardens (12%) and in pet food (7%, differences in total due  
233 to rounding). Total outflows amount to 92 789 t N (with uncertainty estimates ranging from 64 000  
234 to 138 000 t N), 54% of which are attributed to human excretion and 13% to food waste. Also garden  
235 waste (16%), material waste (7%) and waste from pets (10%) contribute, with the latter estimated  
236 just from the inflows of pet food consumed. Considering the sum of all flows, there are more inflows  
237 than outflows accounted for. Overall, the balance difference (surplus) of 33 924 t N corresponds to  
238 27% of total inflows. As discussed in more detail below, this difference is assumed to be caused by  
239 flows that might have been missed in the analysis (mainly material products, but also human body  
240 excretion), or by accumulation of N in the form of durable consumer goods. Energy is not included in  
241 the balance calculation, but with roughly 30 000 t N a<sup>-1</sup> constitutes a significant amount of reactive N  
242 that is emitted to the atmosphere.

243 The following flows turned out to be likely irrelevant: (i) Products from semi-natural vegetation, such  
244 as cut flowers; these could not be quantified separately due to data problems, but in a full NNB, at  
245 least their fertilization would be accounted for within the compartment of agriculture; (ii) metal and  
246 ceramic products, which typically contain very little N ( $N < 0.1\%$ ); (iii) nitrate in drinking water and  
247 food: according to Elmadfa and Burger (1999), an average person in Austria takes in about 69 mg of  
248 nitrate per day in drinking water and food, which sums up to only 50 t  $\text{NO}_3\text{-N}$  for Austria as a whole in  
249 2010, and even less for drinking water alone.

250  
251

**Table 2: Quantified consumer-related N flows in Austria 2010.** UF = uncertainty factor; where no UF is presented, N min and N max are estimated in a simplified manner as the sum of N min and N max of the respective elements.

Inflows	N flow [t N a <sup>-1</sup> ]	UF	N min [t N a <sup>-1</sup> ]	N max [t N a <sup>-1</sup> ]	Outflows	N flow [t N a <sup>-1</sup> ]	UF	N min [t N a <sup>-1</sup> ]	N max [t N a <sup>-1</sup> ]
<b>Food supply</b>	<b>66 155</b>		<b>60 141</b>	<b>72 770</b>	<b>Food waste</b>	<b>11 922</b>	<b>1.33</b>	<b>8 964</b>	<b>15 856</b>
<i>Animal food domestic</i>	20 700	1.1	18 818	22 770					
<i>Animal food from imports</i>	15 868	1.1	14 425	17 455	<b>Human Body Excretion</b>	<b>50 424</b>		<b>41 572</b>	<b>74 261</b>
<i>Plant food domestic</i>	18 694	1.1	16 995	20 563	<i>Human excretion to sewage system</i>	47 157	1.33	38 531	68 158
<i>Plant food from imports</i>	10 894	1.1	9 903	11 983	<i>Human excretion to hydrosphere</i>	3 063	1.33	2 989	5 288
					<i>Atmospheric emissions human body</i>	204	4.0	51	815
<b>Material Products</b>	<b>35 518</b>		<b>23 509</b>	<b>55 837</b>	<b>Material waste</b>	<b>6 046</b>	<b>2</b>	<b>3 023</b>	<b>12 091</b>
<i>Synthetic polymers for product use</i>	11 865	2	5 932	23 729					
<i>Detergents</i>	73	4	18	290					
<i>Textiles, Wearing apparel &amp; Leather</i>	9 437	1.33	7 095	12 551					
<i>Wood &amp; paper products</i>	13 464	1.33	10 123	17 907					
<i>Tobacco</i>	680	2	340	1 360					
<b>Pet food supply (&amp; consumption)</b>	<b>9 355</b>	<b>1.33</b>	<b>7 034</b>	<b>12 443</b>	<b>Waste &amp; excretion from pets*</b>	<b>9 355</b>	<b>1.33</b>	<b>7 034</b>	<b>12 443</b>
<b>N input to private gardens &amp; public green spaces</b>	<b>15 685</b>		<b>8 386</b>	<b>29 922</b>	<b>Green waste &amp; garden waste</b>	<b>15 042</b>	<b>2</b>	<b>7 521</b>	<b>30 083</b>
<i>Mineral fertilizer</i>	2 160	1.33	1 624	2 873					
<i>Compost</i>	13 525	2	6 762	27 050					
<b>Total Inflows</b>	<b>126 713</b>		<b>99 070</b>	<b>170 973</b>	<b>Total Outflows</b>	<b>92 789</b>		<b>64 352</b>	<b>138 082</b>
					<b>N balance (inflows – outflows)**</b>	<b>33 924</b>		<b>34 718</b>	<b>32 891</b>
					<b>Energy</b>	<b>30 075</b>		<b>22 613</b>	<b>40 000</b>
					<i>Heating</i>	2 997	1.33	2 253	3 986
					<i>Electricity</i>	898	1.33	675	1 194
					<i>Transportation</i>	26 180	1.33	19 684	34 820

252

\* outflow assumed from inflow

\*\* assumed to represent residual waste streams

253 **Food.** The most straightforward and uncritical aspect of this study are nitrogen flows related to food.  
254 Data on food supply (rather than actual food consumption) are readily available from reliable sources  
255 (Statistics Austria and FAO) back until the 1960's. Minor differences were detected comparing the  
256 food amounts reported by Statistics Austria and FAO over the time periods, possibly as a result of  
257 errors in data transmission (e.g., FAO reports distinctly higher amounts of pork supply compared to  
258 Statistics Austria – roughly 580 000 t vs. 470 000 t in 2010, respectively). Overall, however, the data  
259 match, and we used the FAO figures due to their consistent reporting format. However, we could not  
260 rely on protein supply data by commodity, which is reported by FAO in addition to mere food supply  
261 data. Here FAO statistics appear inconsistent: N flows derived from food supply data multiplied by  
262 respective protein content are about 35% (for vegetables) and 10-15% (for animal products) higher  
263 compared to flows derived from protein supply data. This is a consequence of the reporting format  
264 which issues zero values for some minor food categories. Thus we refer to FAO's food supply  
265 statistics and the relevant protein contents only. The time trend (Figure 1) confirms observations of  
266 other studies (e.g., Lassaletta et al. 2014; Liu et al. 2014): Over time, the share of animal N supply has  
267 increased from roughly 47% in 1961 to 55% in 2010. Absolute amounts of total N supply have  
268 increased from 47 929 t N in 1961 (22 367 t N from animals, 25 562 t N from plants) to 66 155 t N in  
269 2010 (36 567 t N from animals, 29 588 t N from plants). On a per capita basis, the supply of vegetable  
270 N has decreased slightly from 1961 to 2010 (minus 2%), while the animal N supply has increased by  
271 39%. These figures do not, however, show the losses of nitrogen that occur during agricultural  
272 production and processing of the food, or the food waste on the consumer side. These aspects are  
273 covered by footprints, such as presented by Pierer et al. (2014) who calculated "virtual nitrogen  
274 factors" (VNF) for Austria that give the losses of reactive N along the entire production and  
275 consumption chain per kg N consumed as a final food item. Applying these virtual nitrogen factors  
276 (Pierer et al. 2014) to our results on total food consumption implies a total loss of nearly 150 000 t N  
277 for Austria in 2010. Dividing this amount by the N actually consumed indicates that on average, for

278 each kg of N directly consumed as food, an additional 1.8 kg of N are lost to the environment during  
279 production and processing.

280 **Food waste** in our study is estimated as 11 922 t N in 2010, which matches the estimates for Austria  
281 presented by Gustavsson et al. (2011): 11 833 t N a<sup>-1</sup>; and Monier et al. (2010): 9672 t N from  
282 wholesale and retail, households, food services and restaurants based on national studies; or 9743 t  
283 N from households and other sectors based on Eurostat estimates for 2006. The relatively large  
284 amount of food waste – corresponding to 13% of the quantified outflows – points to a readily  
285 attainable potential of reducing N loss. Avoiding food waste is an issue of growing concern and public  
286 awareness as illustrated by current scientific publications and public campaigns both in Austria  
287 (BMLFUW 2015) and internationally (European Commission 2015; Grizzetti et al. 2013; Gustavsson et  
288 al. 2011).

289 **Human Excretion.** Total excretion from the human body adds up to 50 424 t N, the dominating share  
290 of which enters the sewage system (93.5% of total human body excretion). N excreted by humans  
291 that flows directly to the hydrosphere because of missing connections to the sewage system is of  
292 minor importance (6.1% of total) - sewage connection rates in Austria are considered high (BMLFUW  
293 2012). Atmospheric emissions of ammonia (NH<sub>3</sub>) as determined according to Sutton et al. (2000) are  
294 listed separately here for reasons of completeness, but are insignificant (0.4% of total). Comparing  
295 human excretion with the amount of N from food that is available for consumption (i.e., food supply  
296 minus food waste, 54 233 t N) shows that roughly 4000 t N of outflows are “missing”. This  
297 corresponds to 7% of the inflows and seems to be an acceptable discrepancy. A possible explanation  
298 for this balance difference could be detected on the side of the inflows: It is conceivable that the  
299 amounts of food waste are underestimated, as food waste is very difficult to capture statistically.  
300 Higher amounts of food waste would reduce the amount of food available for consumption and  
301 consequently shrink the gap between food consumption and human excretion.

302 **Material Products.** The main area of balance differences is non-food industrial products: Inflows of  
303 material products amount to 35 518 t N, but material waste is only 6046 t N, which gives a mismatch  
304 of 29 472 t N (or 83% of inflows). Thus, the amount of N in material waste from waste statistics  
305 covers only roughly 17% of estimated material inflows, which is considerably less than the 75%  
306 assumed by Gu et al. (2013). Uncertainties related to this estimate are high, but cannot fully account  
307 for the detected difference, as the covered total waste streams are smaller than any one of the three  
308 main material classes covered as inflows. This indicates that besides stock changes (i.e., accumulation  
309 of material products in human settlements), there must exist residual waste streams which are not  
310 covered by the method applied. Residual waste streams are likely to include waste that is not  
311 accounted for in the waste statistics and/or not directly assigned to households, e.g. end-of-life  
312 vehicles which contain synthetic polymers, the N content of which cannot be estimated reliably on  
313 the waste side. Furthermore, there might be a certain fraction of material products that have been  
314 incorrectly assigned as inflows to households rather than industry, and the respective outflows  
315 would have to be found in statistics on industrial waste (e.g., polymers that are used for the  
316 construction of manufacturing machines rather than consumer goods). Statistical information that  
317 clearly distinguishes between material use by households and industries is scarce. However,  
318 additional data collection endeavors at this level of detail will be useful only if the information gained  
319 can also be used for other purposes besides N budgets. For many (scientific) questions, the existing  
320 material flow accounting may be sufficient (Fischer-Kowalski et al. 2011).

321 With regard to the inflows of material products, our results translate to 4.2 kg N cap<sup>-1</sup> a<sup>-1</sup> (ranging  
322 between 2.8 and 6.7 kg). This corresponds well with Obernosterer and Reiner (2003), who used a  
323 different approach but estimated N flows of between 3.7 and 6 kg N cap<sup>-1</sup> a<sup>-1</sup> for durable consumer  
324 goods such as furnishing and 0.6–1 kg N cap<sup>-1</sup> a<sup>-1</sup> for non-durable consumable goods such as  
325 packaging and detergents.

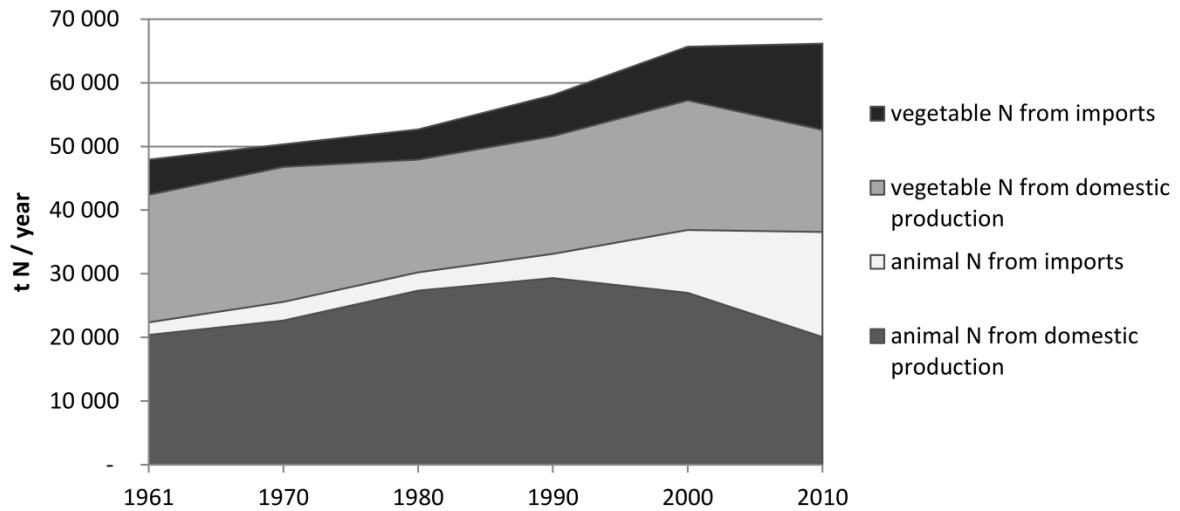
326 **Pets.** N inflows as pet food have been assumed as a separate flow quantified based on protein  
327 requirements and feeding recommendations. It might be argued that pet food partly stems from



328 human food (or human food waste), which would reduce the N food supply and thus lower the  
329 amount of total inflows for the balance. However this problem can be neglected, as the amount of N  
330 from pet food is in the same order of magnitude as the margins of uncertainty for food supply. Waste  
331 and excretion from pets could not be quantified independently, and was set to match with pet food  
332 supply.

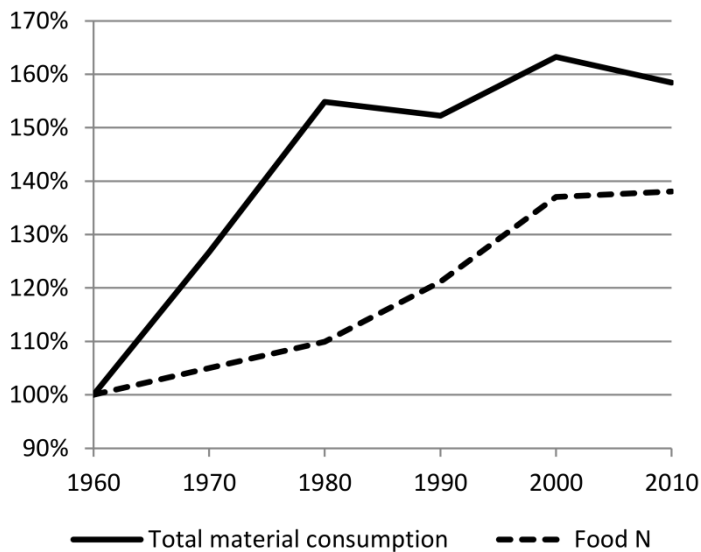
333 Within the sphere of **private gardens and public green spaces**, the independently determined  
334 outflows (i.e., green waste and garden waste based on waste statistics) do match well with the  
335 inflows (i.e., mineral fertilizer and compost). A potentially missing outflow, however, is food  
336 harvested from private gardens, which cannot be included due to lacking data, and is assumed to be  
337 small.

338 **Temporal trend.** Figure 1 shows the development of nitrogen flows related to food supply in Austria  
339 from 1961 to 2010. This corresponds to food consumption and food waste by Austrian consumers  
340 from both domestic production and imports. It does not include food exports, which are not relevant  
341 for consumption. Figure 2 combines this time trend of food supply N with trends of total material  
342 consumption. As no information on historical material N contents and flows is available, only the  
343 trend of total domestic material consumption as assessed by standard material flow accounts  
344 (Petrovic 2014) is shown, which not necessarily fully reflects trends of N contained in such material.  
345 Furthermore, it has to be considered that “domestic consumption” in material flow accounting  
346 includes the use of different natural resources, but does not directly correspond to material  
347 consumption by consumers or households. Still, the trends for food and materials (Figure 2) indicate  
348 the growing importance of material consumption in comparison with food and provide a valuable  
349 starting point for comparison.



350

351 **Figure 1: Development of food N supply in Austria: 1961 – 2010**, corresponding to food consumption and food waste from  
 352 domestic production and imports, respectively. (Source: own calculation based on FAO 2014a, 2014b, 2014c; Statistik  
 353 Austria 2012b)



354

355 **Figure 2: Temporal trends of food N and total material flows, representing N in materials. 100 % = 1960.** (Food: own  
 356 calculations based on Statistik Austria 2012b; FAO 2014a, 2014b, 2014c. Materials: based on trends from material flow  
 357 accounting (Petrovic 2014 – without direct reference to nitrogen contents.)

## 358 4. Conclusion

359 The present analysis provides a budget of N flows related to consumers in Austria. Detailed  
 360 scrutinizing of otherwise under-represented and poorly investigated aspects reveals the importance

361 of N flows related to material products, private gardens and public green spaces, as well as pets. N  
362 flows related to food are rather well constrained and remain the single most important item within  
363 the boundaries of this analysis. Comparing independent datasets of flows in and out of the consumer  
364 sphere helps to support the available data and improves their reliability.

365 Valuable information can also be drawn from an observed discrepancy, pointing to a knowledge gap  
366 within national nitrogen budgets: With regard to material products, our results indicate unaccounted  
367 streams of material waste, or an unexplained stock change. Here the present data is not sufficient to  
368 fully explain the fate of N. In general, this proves that the systematic consideration of such flows in  
369 nitrogen budgets makes sense and should be pursued.

370 The knowledge gap regarding material products not only refers to the quantities, but also to the  
371 chemical form of the substances involved. Potentially, the environmental relevance of the missing N  
372 flows is very limited, as N may be enclosed in a stable form and not become environmentally active.  
373 Additional scrutiny will be needed to better understand the missing quantity and quality of N flows.  
374 This may be achieved by a look at the broader system, i.e. the connection between the segment  
375 analyzed here and the other “pools” of a nitrogen budget on a national basis (UN ECE 2013).

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380 scholarship received from the University of Graz.

## 381 **Appendix**

382 **Table A 1: Overview on main data sources used to determine mass flows**

<b>Flow</b>	<b>Main data sources</b>
Food supply	Statistik Austria 2012b, FAO 2014a, 2014b
Food consumption, food waste	Umweltbundesamt 2012
Synthetic polymers for product use	ISOPA 2003, Plastemart 2007a, 2007b, IHS chemical sales 2010;

	OCI Nitrogen 2011; Raimar 2012
Wood & paper	Statistik Austria 2012a; Austropapier 2013; FAO 2014c
Textiles & leather	Statistik Austria 2012a; FAO 2014c
Detergents & surfactants	Statistik Austria 2012a
Pet food, pet waste	Sutton et al. 2000; Hand et al. 2002; Methling and Unshelm 2002; Weiss et al. 2003; FEDIAF 2010;
Garden fertilizer, garden waste, compost	BMLFUW 2010; Umweltbundesamt 2012; Egle et al. 2014; International Fertilizer Industry Association 2014; ARGE Kompost & Biogas Österreich 2014 ; Colón et al. 2010
N excretion & emission by human body	Sutton et al. 2000; BMLFUW 2012
Energy	Statistik Austria 2011

383 **Table A 2: N contents of products and substances.**

Item	N content [%]	Sources / Comments
Food Products average total	0.84	Souci et al. 2008; Heldstab et al. 2010
Animal-based food average	1.12	
Plant-based food average	0.64	
Food Waste	0.84	approximated by the average of all food supply in 2010
Polymers		
Polyamide (nylon, PA66, $(C_6H_{11}NO)_n$ ; perlon, PA6, $(C_{12}H_{22}N_2O_2)_n$ )	12	stoichiometry
Polyurethane (broad distribution)	10	estimate
Melamine (melamin formaldehyde, $(C_7H_{12}N_6)_n$ )	47	stoichiometry
Detergents (cationic surfactants)	2.1	mass weight representative calculated based on an esterquat (quaternary ammonium cations with a relative molecular weight of 648 g/mol).
Textiles & Wearing apparel		
made of crop fibers	0.2	includes cotton, cellulose, flax, plush, velvet, fleece, chenille; estimate for cotton based on Bode et al. 2007
made of animal hair or animal fibers	15	e.g. wool, silk, cashmere, fur, felt; these consist mainly of fibroin, sericin, keratin, collagen which are mainly proteins (assumption: 95% protein)
leather and related products	15	Consists mainly of collagen, with an assumed protein content of 95%
Wood and wood products	0.1	Leppälahti and Koljonen 1995; Heldstab et al. 2010
Paper and paper products	0.1	Leppälahti and Koljonen 1995; Heldstab et al. 2010
Tobacco	4.0	Butorac et al. 2004
Compost	1.45 (0.6 – 2.3)	BMLFUW 2010
Green Waste	0.8	Kumar et al. 2010; Vaughan et al. 2011

384

385 **Table A 3: Estimated consumption of Polyurethanes (PU), Polyamides (PA) and Melamine in 2010 (PU and Melamine) and**  
386 **2007 (PA).**

	Polyurethanes (PU)	Polyamides (PA)	Melamine/Urea Formaldehyde Resins (MF, MUF, UF)
Demand worldwide [million t]	14	7	1.2
Demand Europe [million t]	5	3.08	0.384
Sources	Raimar 2012	Plastemart 2007a, 2007b	OCI Nitrogen 2011; IHS chemical sales 2010
N Consumption Europe*	676	499	244

[t N/million inhabitants]			
N Consumption Austria [t N]	5649	4176	2039
*) Own calculations, based on European population of 740 million; N content factors as given in Table A2			

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## Highlights

National nitrogen (N) budgets usually focus on food and other agricultural products.

We investigate frequently neglected flows of nitrogen related to consumers.

Food consumed (and human excretion) account for over half of the N flows in 2010.

Non-food industrial products account for 28% of consumer N flows in Austria.

More complete nitrogen budgets need to consider non-food consumer-related aspects.