Food and feed supply and waste disposal in the industrialising city of Vienna (1830–1913): a special focus on urban nitrogen flows

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Abstract Taking an urban metabolism perspective, this article investigates food and feed consumption as well as flows of nitrogen in the city of Vienna during the industrial transformation. It addresses the question of the amount of agricultural products consumed in the city and their nitrogen content, their origin and their fate after consumption. Changes in dietary nitrogen flows in nineteenth century Vienna are embedded in the context of a socio-ecological transition from an agrarian to an industrial socio-metabolic regime. Similarities and differences in the size and dynamics of urban nitrogen flows in Vienna and Paris are discussed. Critical reading of historical sources and historical material flow accounting are the methodological backbone of this study. Between 1830 and 1913, inflows of dietary nitrogen into the city increased fivefold. Throughout the time period under observation, the urban waterscape was the most important sink for human and animal excreta. The amount of nitrogen disposed of in the urban waterscape via urban excreta increased sevenfold. The average daily consumption of nitrogen per capita was very similar to that in Paris, but the composition of foodstuff differed. In Vienna, the share of meat in food consumption was considerably higher. Both cities had to face the challenge of increasing output flows. However, urban

authorities in Vienna and Paris came to different solutions of how to deal with this challenge. Besides institutional settings, the specific geomorphology of the cities as well as biogeographic factors such as the absorption capacity of the Danube in Vienna and the Seine in Paris mattered.

Keywords Urban metabolism · Socio-ecological transition · Nitrogen · Food · Long-term socio-ecological research · Vienna

Introduction

Changes in global biogeochemical nitrogen cycles have been causing environmental problems on local as well as on global scales (Rockström et al. 2009; Sutton et al. 2011). Rockström et al. (2009) define the global biogeochemical nitrogen cycle as one of nine planetary boundaries. Transgressing these boundaries can increase the pressure on the earth system in a way that may lead to abrupt global environmental change. Human interferences with nitrogen cycles have caused drastic changes in aquatic and marine ecosystems induced by eutrophication or acidification. Release of reactive nitrogen contributes to air pollution and soil acidification; it induces changes in terrestrial ecosystems and biodiversity, and it has an effect on the greenhouse balance (Sutton et al. 2011). Nowadays, industrial fixation of atmospheric N_2 to ammonia, agricultural fixation of N_2 via cultivation of leguminous crops, fossil fuel combustion and biomass burning are the main human driven processes that cause modifications of global N cycles (Rockström et al. 2009). A century ago, the availability of reactive nitrogen was a constraint for human action. Reactive nitrogen was mainly needed as fertiliser for food production and for the fabrication of munitions

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(Sutton et al. 2011). Before the introduction and wide spread application of industrial fertilisers, maintaining soil fertility was a limiting factor for agricultural production (Sutton et al. 2011). With every crop harvest, plant nutrients like nitrogen are removed from the field and consumed in often distant places such as urban agglomerations. With the transition from an agrarian to an industrial socio-metabolic regime (Fischer-Kowalski and Haberl 2007) in the nineteenth century, cities in Europe were growing fast and so was their demand for food and feed. Ever larger amounts of nitrogen were withdrawn from the agricultural hinterland and concentrated in the urban centres. There the disposal of a growing amount of urban excrements and waste posed challenges. In many cases, urban waterscapes served as sinks for excrements and waste, causing sanitary and ecological nuisances. Prominent chemists like Justus von Liebig in Germany and Jean-Baptiste Boussingault in France discovered nitrogen to be an essential plant nutrient. They called for the collection of all urban excrements and giving the nutrients contained in it back to the fields in order support the increase in agricultural production (Liebig 1878, first edition 1840). In the nineteenth century, the question of how to improve agricultural productivity in order to feed a growing urban population and how to deal with urban excrements were widely debated among agriculturalists, chemists, hygienists and urban authorities (Barles 2007a; Winiwarter 2001). Different strategies for coping with the above-mentioned challenges were pursued in different cities.

The paper takes a long-term socio-ecological (LTSER) perspective. LTSER tries to understand how nature, society and culture have been intertwined for millennia and is concerned with contemporary societal and environmental challenges (Singh et al. 2013). In this paper, the city of Vienna serves as a case study to investigate the dynamics of urban nitrogen flows during industrialisation. The paper presents data on the amount of nitrogen contained in food and feed consumed in the city between 1830 and 1913. It assesses the location of the nitrogen-supplying hinterland and the fate of nitrogen after its consumption. It compares the case of Vienna with the city of Paris and analyses why different strategies for coping with output-related problems were chosen in the two cities. This comparison builds on a study on dietary nitrogen flows in nineteenth century in Paris (Barles 2007a). The concepts of urban metabolism (Wolman 1965; Tarr 2002; Barles 2007a) and socio-ecological transitions (Fischer-Kowalski and Haberl 2007) enable a deeper understanding of urban change and its impacts on the environment (Barles 2007a). Urban metabolism builds on the idea that cities require material, energy and water for their functioning. After its use, the resource inputs leave the city again in form of waste and emissions. The concept of urban metabolism stresses the

strong link between urban resource use and output flows. It allows the investigation of key interactions between socio-economic systems and their natural environment and links different aspects of human resource use with impacts on ecosystem functioning: Changes in the urban biomass metabolism with regard to food and feed consumption have an impact on biogeochemical nutrient cycles. As the focus of LTSER is on the long-term evolution of human environment interactions, the application of the metabolism concept can contribute important insights for LTSER (Singh et al. 2013). Several studies applied the concept of urban metabolism to investigate nutrient flows in urban systems (Baccini and Brunner 1991; long-term studies: Barles 2007a; Schmid-Neset 2005; Svirejeva-Hopkins et al. 2011; Morée 2013). Paris is a well-studied example when it comes to long-term studies on nutrient flows: Next to Barles (2007a), who has quantified urban nitrogen flows, other studies have investigated city–hinterland relationships and the environmental imprint of food consumption of Paris (Billen et al. 2012, 2009; Chatzimpiros and Barles 2013). Furthermore, the output side of urban metabolism and emissions to the water have been studied extensively (Billen et al. 1999).

The city of Vienna, like other European urban centres, underwent a profound transformation in the respective time period. Its population grew by a factor of 7 from 318,000 inhabitants in 1830 to more than 2.1 million inhabitants in 1913 (Gierlinger et al. 2013). The second half of the nineteenth century was characterised by urbanisation, industrialisation and economic growth. Vienna underwent the energy transition from biomass to large-scale use of coal (Krausmann 2012). The demand for food, as well as feed for draft animals and other livestock, increased steeply. On the one hand, this development increased the nitrogen imprint on the agricultural hinterlands, and on the other hand, it raised ecological pressure on urban waters.

A comparison of the nitrogen metabolism of Vienna and Paris is fruitful for several reasons. One very practical reason for comparing Vienna with Paris is that several studies on dietary nitrogen flows and the sanitary question in Paris in the nineteenth century already exist (see above). Both cities were transforming fundamentally in the nineteenth century. They became industrialised urban centres. In Paris, the urbanisation and industrialisation process started a bit earlier than in Vienna. In Vienna, the transformation accelerated in the second half of the nineteenth century (Krausmann 2012). In both cities, heavy debates on how to increase agricultural production, how to cope with the increasing amount of urban excrements, how to deal with river pollution and sanitary nuisances took place, but different solutions for the posed problems were aimed at. The same macro-processes such as industrialisation, urbanisation and the energy transition took place in both

cities, but still different decisions with differing impacts on the city and its waterscape were made on the small scale. Tracing back these differences and similarities between the two cities contributes to a better understanding of how nature, society and culture have been intertwined during this transition process.

The first part of the paper deals with the calculation of urban nitrogen flows. It describes how data on dietary nitrogen flows were compiled, and what sources were used. The next section presents results on food and feed consumption and urban outflows. The third part is a comparative section on dietary nitrogen flows in Vienna and Paris. Finally, conclusions on changing nitrogen flows in the city of Vienna during the industrial transformation are drawn.

Methods and sources

The historical approach to study the development of the metabolism of the city of Vienna and in particular the flows of nitrogen combines qualitative and quantitative methods. Inflows of nitrogen contained in food and feed into the urban system, as well as output flows of nitrogen contained in human and animal excreta were estimated using principles from material flow analysis. The literature review and source criticism provide the basis for the quantification of dietary nitrogen flows and the discussion of the evolution of the sewage disposal system. A similar approach was applied by Barles (2007a) for Paris and Schmid-Neset (2005) for the Swedish city of Linköping.

System boundaries

In urban metabolism studies (Krausmann 2012; Barles 2009), a city is conceived of as socio-economic system that exchanges materials and energy with its natural environment and other socio-economic systems. The urban system is defined by its boundary to the natural system and its administrative boundary and follows basic system boundary principles of material flow analysis (Niza and Rosado 2009; Krausmann 2012). Livestock is considered part of the socio-economic system; therefore, nitrogen contained in feedstuff and animal excreta is taken into account as socio-economic flow. The administrative boundary of the city of Vienna changed several times during the time period under consideration (1830–1913). Until 1850, the size of the actual city comprised only around 2.8 km² (see Fig. 1). Already, in 1704, a fortification wall, the so-called *Linienwall*, was erected around the city and its suburbs. This fortification wall soon lost its military significance, but it served as the city's tax boundary. In 1850, the suburbs within the *Linienwall* were incorporated into the city, which meant an extension of the city to 60 km² (see

Fig. 1 Hydrographic map of Vienna in its different boundaries. The blue lines mark the river Danube and its two largest tributaries in the situation after the great Danube regulation in the 1870s. *a*) present-day administrative boundary of Vienna comprising 440 km². *b*) Viennese tax boundary 1891–1913. *c*) the so-called *Linienwall* which served as the boundary for the consumption tax (*Verzehrssteuer*) between 1829 and 1890 comprising an area of 60 km². It also included the area between *Donaukanal* and the main arm of the Danube. *d*) City wall until 1850 comprising an area of 2.8 km². (1) Main arm of the Danube. (2) *Donaukanal* (graphic design by Friedrich Hauer and Sylvia Gierlinger, based on a hydrographical map of MA 45 Wiener Gewässer)

Fig. 1). The city was growing fast in the nineteenth century. In 1891, another extension of the administrative and the tax boundary took place. With the incorporation of the suburbs, a reform of the taxation system took place and the territory of the tax boundary got extended to the incorporated suburbs (Hauer 2010), increasing the territory of Vienna to 178 km². With the incorporation of the suburbs in 1891, population numbers jumped from 817,000 to 1,365,000 inhabitants. Further areas north of the Danube were annexed to the city in 1904/5, but the tax boundary was not extended until the urban consumption tax was finally abolished in 1921/22. The city of Vienna reached its present-day size of 440 km² after WWII. The tax boundary of the city—which differed from the administrative boundary—was adopted as system boundary to study urban metabolism, as it was more stable. In the observed period, it was extended only once in 1891 from 60 to 178 km². In this study, population and livestock numbers always refer to the area within the tax boundary. Between 1830 and 1890, this is the area within the so-called *Linienwall*, with population numbers rising from 317,000 to 817,000, and from 1891 until 1913, the area includes the incorporated suburbs. Population numbers rose from 1,370,000 to slightly more than 2 million between 1891 and 1913. For comparison over time and with Paris, per capita numbers have been calculated.

Inflow of food and feed

The amount of food and feed available for consumption within the tax boundary was calculated for the time period from 1830 until 1913. Whenever possible, numbers were taken from historical sources. Otherwise, estimation procedures were applied. Comprehensive data on food inflow deriving from historical sources only exist for the time period between 1830 and 1890. Afterwards, only numbers on slaughter animals, meat, milk and alcoholic beverages were given. The missing numbers on inflow of dietary nitrogen between 1891 and 1913 were extrapolated by multiplying the per capita 5 years average (1886–1890) value of cereals and other foodstuff of animal and vegetal origin with population numbers. The amount of meat available for consumption in the city was calculated based on numbers of imported slaughter animals, information on the slaughter weight and the share of bones of the respective animals (see Online Resource S1). Data on food and feed inflow given in fresh weight were converted to its nitrogen content by applying commodity-specific conversion factors (Billen et al. 2009; Barles 2007a; FAO 2001).

The amount of feed reported in historical sources (oats, hay and straw for feed) seemed to be too low for the period after 1860 for meeting the demand of urban livestock (mostly draft animals, but also some milk cows). One explanation for this could be that the feed demand was met by other feedstuff than oats, hay and straw. There is evidence that milk cows were fed with waste from breweries (Handels- und Gewerbekammer in Wien 1867). From 1890 until 1913, no data on feedstuff were reported; therefore, feed demand was estimated based on assumptions on average live weight of urban animals, typical daily feed intake ratios and nitrogen content of feedstuff (Krausmann 2008; Hitschmann and Hitschmann 1920; Billen et al. 2009).

Total food and feed inflow were aggregated to five categories: cereals (for human consumption), meat, feed, other foodstuff of animal origin and other foodstuff of vegetal origin. Cereals include grain, flour, bread and all kind of cereal products. Meat includes meat from cattle, veal, pigs, piglets, sheep, goat, chicken, pigeon, turkey, rabbits and all kinds of meat products. It does not include (even if mentioned in historical sources): game like wild boar, deer, pheasant and small birds. Other foodstuff of animal origin includes milk, butter, lard, cheese, eggs and fish. All other foodstuff of vegetal origin includes vegetables, fresh and dried fruit, nuts, potatoes, rice, pulses, beer, wine and must.

Outflow of dietary nitrogen to the urban rivers

Output flows of dietary nitrogen to the urban rivers were calculated based on information about the disposal system and on nitrogen excretion rates by humans and their draft

animals (see Gierlinger et al. 2013). Excretion rate of humans was assumed to be 10 gN/cap/day; excretion rate of horses was assumed to be 113 gN/head/day (Barles 2007a). The resulting numbers for humans were multiplied with numbers on the share of houses connected to sewers or open drains. In 1830, around 85 % of houses were connected to sewers or open drains that discharge into one of the many streams that were traversing the city. The share rose to 91 % in 1890; it declined after the incorporation of suburbs in 1891 and rose again to 85 % in 1913 (see Gierlinger et al. 2013). Based on a literature review (see Gierlinger et al. 2013), it was assumed that only a small fraction of horse manure (5 %) was disposed into urban waters.

Sources

Main source for the gathering of data on food and feed supply were records of the consumption tax. In the year 1829, a toll on consumption (*Verzehrssteuer*) was introduced in most parts of the Austrian empire. The examples of the consumption tolls in Italy (*dazio consumo*) and France (*droit d'octroi*) served as models for the introduction of this tax on goods of everyday consumption (Hauer 2010). Transcripts and the critical assessment of sources (Hauer 2010; Hauer et al. 2012) were the basis for the calculation of urban nitrogen flows (further information in the Online Resource S2). Missing or misleading data on milk, beer, cereal and vegetable consumption were complemented by data from the statistical periodical *Statistische Monatsschrift* (Pizzala 1881) and Sandgruber (1982) and extrapolation of per capita values. Data on slaughter weight of cattle derive from the administration office of the Viennese markets (Marktamt der Stadt Wien 1878–1890). Data on livestock numbers were gathered in the course of the census from the year 1857 onwards. Data were published by the statistical central commission (K.k. statistische Central-Commission 1871, 1882) K.k. Ministry of the Interior (1859), Sedlazeck 1891 and municipal authorities of Vienna (MSW 1901, 1912). Information on changes in the disposal system was gathered from yearbooks of urban health authorities (WSTP 1864–1913) and the technical literature (Wodicka 1900; Podhagsky 1892; Kortz 1905) from the late nineteenth and early twentieth centuries (see Gierlinger et al. 2013).

Results and discussion

Food and feed consumption

Meat

The total meat consumption expressed in its nitrogen content increased fivefold in the whole time period—from slightly

Fig. 2 Meat consumption in Vienna in the years 1830–1913 **a** in tons of nitrogen per year and **b** in grams of nitrogen per capita per day. Data based on Hauer et al. 2012, own calculation, see text

Table 1 Consumption of foodstuff in Vienna in the years 1830, 1870 and 1913. Data based on Hauer et al. 2012, Pizzala 1881, MSW various years and Sandgruber 1982

	1830*		1870		1913*	
	kg/cap/yr	gN/cap/d	kg/cap/yr	gN/cap/d	kg/cap/yr	gN/cap/d
Cereals	160	7.94	145	7.18		
Beer**	105	0.14	166	0.23	148	0.20
Wine**	60	0.06	37	0.03	34	0.03
Must**	8	0.01	3	0	3	0
Meat	92	8.55	75	7	74	7.16
Fish	1.9	0.18	1.73	0.16	1.54	0.15
Milk**	56	0.77	80	1.09	153***	2.09***
Cheese	4.6	0.15	2	0.22		
Eggs	145	0.42	79	0.25		
Butter, lard	4.6	0.02	4	0.02		
Vegetables	60	0.65	93	1.02		
Fruits fresh	26	0.07	32	0.09		
Fruits dry, nuts	1.9	0.01	1	0.01		

* 5 year average; ** l/cap/yr; *** 5 year average 1906–1910

more than 1,000 tons of nitrogen per year in 1830 to more than 5400 in 1913 (see Fig. 2a). Slaughter cattle used to be the most important source of animal products throughout the whole time period. But the importance of cattle decreased over time. Around 1830, more than 70 % of the meat consumed in Vienna derived from cattle and veal. This share decreased to around 50 % in the late 1880s. With the incorporation of the suburbs into the city, the share of beef in meat consumption increased slightly, but it started to decline again to slightly over 50 % in 1913. Between 1869 and 1891, the share of cattle went down and meat products (processed meat) got more important. Among the meat products, products deriving from cattle made up the greatest part (more than 80 % in the year 1880, see MSW 1884). In 1891, one-third of the meat consumed in Vienna derived

from meat products. In the suburbs, more pig meat was consumed than in the city. For that reason, the share of pig meat on total meat consumption jumped up after the incorporation of the suburbs in 1890 (Fig. 2a). By the year 1913, the share of pork meat reached 27 %. Over land transport of pigs was more complicated than for cattle. With the rising significance of rail transportation in the second half of the nineteenth century and new feeding techniques, more pigs were brought to the Viennese market (Sandgruber 1982). The consumption of beef can also be interpreted as an indicator of wealth. The bourgeoisie was concentrated in the city. With the extension of the city borders, suburbs with a less wealthy population became part of Vienna. Per capita consumption of meat slightly decreased from around 92 kg per capita in 1830 to around 74 kg in 1913 (see Table 1). This corresponds to 8.6 g nitrogen per capita and day in the 1830s and around 7.2 g nitrogen per capita and day around 1913 (see Fig. 2b).

Cereals and other foodstuff

Cereals used to be the second most important foodstuff with regard to nitrogen inflows. Around 1830, the Viennese consumed on average 160 kg of cereals per year, which corresponds to 7.9 g of nitrogen per capita and day (see Table 1). Cereal consumption per capita was slightly decreasing until 1890. Nitrogen input into the city from other foodstuff was rather small. The consumption of fish only played a minor role. In 1830, 1.9 kg of fish was consumed per capita and year, which corresponds to only 0.18 g of nitrogen per capita and day. The amount of fish consumed on average by the Viennese went even down until 1913 to only 1.54 kg per capita and year. Fish was very expensive compared with other foodstuff and thus mainly consumed by wealthy people (Sandgruber 1982). Nevertheless, a transition from expensive freshwater fish to cheaper seawater fish that was transported to Vienna by railways took place in the nineteenth century. This change

did not affect the amount of fish consumed (Sandgruber 1982; Pizzala 1881). As mentioned earlier, the amount of cheese, egg, vegetables and fruits might be somewhat underestimated due to a small tax-free amount and production within the tax border. Consumption of beer and wine was quite common. Although the consumption of wine went down from 60 litre per capita per year in 1830 to 34 litre per capita in 1913. While relevant in terms of nutritional value, expressed in its nitrogen content, the alcoholic beverages were not very important. They make up only a small fraction of the total consumption of nitrogen (see Table 1).

Total food and feed consumption

Comprehensive data on food and feed inflows deriving from the consumption tax only exist for the time period between 1830 and 1890. After the incorporation of the suburbs in 1890, just part of food inflows was covered by the consumption tax (meat and alcoholic beverages). Between 1830 and 1890, the total amount of nitrogen contained in food and feed used in the city of Vienna rose 2.2-fold: 3,000 tons of nitrogen in 1830; more than 6,500 tons of nitrogen in 1890 (Fig. 3a). This increase seems to be too low when considering that in the last decades before the annexation of the suburbs, the city and the suburbs were already grown together and functionally connected. Throughout this time period, meat makes up around one-third of total nitrogen consumption. The share of cereals was at around one-third at the beginning of the observed time period and was down to roughly 25 % in 1890. Feed contributed around 20 % to total nitrogen flows throughout

the time period (see more in the Online Resource S3). The share of other foodstuff from animal origin was rather small. It was 3 % in 1830 and stayed the same until 1890. Other foodstuff of vegetal origin was small in the beginning (slightly more than 9 %) but increased to around 14 % in the 1880s. Per capita apparent consumption of nitrogen from food was around 20 g of nitrogen per capita and day in the 1830s and slightly decreased to around 16 g of nitrogen per capita and day in the 1890s (Fig. 3b). This decrease holds true for all three food categories. There are several interpretations possible, and a combination of them is reasonable for explaining this decrease; one explanation is that with the merging of the city and the suburbs and the higher prices for food within the city wall, an ever increasing amount of food was consumed outside the tax border in the many taverns along the *Linienwall*. This is part of the explanation given by the chair of the imperial statistical commission (Pizzala 1881). Another explanation is that with the increase in a rather poor labour class in this period of early industrialisation, the general nutritional conditions in Vienna decreased. Pizzala (1881) speaks of an increasing impoverishment of the Viennese over the past 50 years. Theoretically, it could also be possible that food processing got more efficient in that time period, and for that reason, the losses between food inflow and food intake declined.

From 1890 until 1913, the total amount of nitrogen contained in food and feed increased to 16,400 tons. This was quite a large amount of nitrogen withdrawn from the agricultural hinterland to meet Vienna's food and feed demand. It was about one quarter of the nitrogen returned to the agricultural fields in current territory Austria by

Fig. 3 Total food and feed consumption in Vienna in the years 1830–1890 **a** in 1,000 tons of nitrogen per year **b** in grams of nitrogen per capita per day. Data based on Hauer et al. 2012, Sandgruber 1982, own calculation, see text

manuring or about the same amount of nitrogen fixed by leguminous crops (Krausmann 2012). The agricultural hinterland of Vienna went far beyond the borders of present-day Austria, especially for the consumption of meat and cereals. Already, in the middle ages, Hungary played an important role for the provision of slaughter cattle for Vienna. At the beginning of the nineteenth century, cattle came from lower Austria, the province surrounding Vienna, Hungary and Moravia, a region in present-day Czech Republic (Oppl 1981). In 1880, slightly more than 50 % of slaughter cattle for the Viennese market came from Hungary, 22 % from Galicia, a historical region in south eastern Poland and western Ukraine, only 6 % from Lower Austria and the remaining 17 % from all other regions (MSW 1880). In the first half of the nineteenth century, cereals were mostly provided by the agricultural regions west and east of Vienna in the fertile Danube basin. A considerable part came from north east Hungary (Oppl 1981; Krausmann 2012). Cereal was brought to Vienna on horse carts or via the Danube and its feeders. Before the introduction of steamship transport of grain from downstream was problematic, still it took place. The ships went upstream with the help of horses pulling the ships (Oppl 1981). After 1850, steamship traffic gained in importance, especially for the transportation of grain (Gierlinger et al. 2013). The amount of grain transported to Vienna from downstream exploded after the great Danube regulation in the 1870s: from around 450 tons in 1835 to more than 300,000 tons in 1889 (Winckler 1870; MSW 1889). Regions as far away as Romania served as provider of grain for the city of Vienna. Bringing back the nutrients contained in urban sewage to regions, this far away obviously poses a challenge.

The fate of nitrogen after consumption

We now have a good picture of the amount of the inputs of nitrogen contained in food and feed into the urban system. But where did it go to? More than 99 % of the nitrogen that is consumed via food leaves the adult human body with excreta (85 % urine, 11 % faeces, 4 % sweat) (Baccini and Brunner 1991). In total, the Viennese population excreted an amount of 1,160 tons of nitrogen contained in their excreta in the year 1830 (Gierlinger et al. 2013). This number rose to more than 7,300 tons in 1913. Furthermore, 205 tons of nitrogen was produced by the 5,000 horses in 1830. This amount increased to around 1,500 tons in 1913.

Most of human excreta were disposed of into the urban waterscape throughout the nineteenth and early twentieth centuries (see Gierlinger et al. 2013). The disposal practice was different for animal and human excreta. Animal excreta were a valuable resource. Animal droppings were collected and even sold on the market (MSW 1883–1913). It can be

assumed that most of solid animal excreta were reused as manure in periurban agriculture. Fractions of the liquid part were disposed into the urban sewers or directly into the small streams traversing the city, part of it got lost via leaching and runoff. Around 1830, most of human excreta got disposed into the urban waterscape. The Viennese made use of the cities convenient geomorphological situation on the easternmost foothills of the Alps, which meant that many small streams traversed from the Vienna forest in the west to the Danube in the east with a comparatively steep gradient. These streams served as a quasi-natural disposal system in the nineteenth century. But the drawbacks of this system which depended to a large extent on weather conditions became more and more obvious with urban growth. Like in many other cities, debates on the best way for disposing sewage and excrements emerged with urban growth. Referring to Justus von Liebig and the contemporary advancements in agrochemistry, the economist Fürst (1863) published a memorandum where he advocated the use of urban excreta for fertiliser production in order to guarantee soil fertility around Vienna and thus a rich agricultural production. Later, engineers like Wodicka (1900) and Podhagsky (1892) and the agricultural ministry proposed the construction of sewage farms in Marchfeld, a region east of Vienna, in order to keep the urban waters clean and create a vegetable garden for the city of Vienna. None of these projects was realised. In the 1860s, the use of human manure for fertiliser production was even prohibited in the urban area of Vienna for sanitary considerations. Exemptions were made for peripheral regions of Vienna, which showed more agricultural characteristics (WSTP 1864–1913). Urban health authorities rejected several proposals for building fertiliser production sites for sanitary considerations (WSTP 1864–1913). In a report on the agricultural situation in Lower Austria, the Chamber of Commerce blamed the loss of fertiliser to the urban waters but at the same time stated that the need for fertiliser in the immediate surroundings of Vienna was not given due to the high numbers of milk cows around Vienna, which would produce enough manure for crop production in the hinterland; transportation of urban excrements further away was perceived as too expensive (Handels- und Gewerbekammer in Wien 1867; for more details, see Gierlinger et al. 2013). Instead, a combined water-born sewage system was constructed. The small streams were vaulted and tunnelled and thus incorporated into the sewage network, and intercepting sewers were installed along the larger streams. This disposal system was favoured by urban health authorities and finished in its basic structure at the beginning of the twentieth century (Gierlinger et al. 2013). The sewage of almost the entire city was discharged into the river Danube more or less untreated. In total, around 6,600 tons of nitrogen was disposed into the river Danube in 1913 (compared with 900 tons in 1830). In a

comprehensive study with hydrologic and chemical analyses of the water of the Danube conducted by the hygiene institute of the University of Vienna (Brezina 1906), the discharge of untreated sewage was justified with the argument of sufficient self-purification of the river Danube.

Dietary nitrogen flows in Vienna and Paris: a comparison

Vienna and Paris are both landlocked cities. Before the dominance of steam-driven transportation (railroad, steamships) in the second half of the nineteenth century, the supply of food and feed for the most part came from the immediate surroundings of the city. In both cities, the waterways played an important role for urban supply, as they provided an economically and energetically feasible way for the transportation of bulk materials, mostly from the above stream hinterland (Billen et al. 2012; Gingrich et al. 2012). Meat, in particular beef, came from regions further away than other foodstuff before the railway and steamship period: Slaughter cattle transported itself to the city on foot. In 1786, meat for the supply of Paris originated from regions such as Normandy and Marche-Limousin, averaging roughly 255 km distance to Paris (Billen et al. 2012). Cereals were transported to Paris from an average distance of 110 km, fruits and vegetables around 87 km. In Vienna fruits, vegetables and milk were produced in the ultimate surroundings of the city; the main staple crops came from the agricultural regions East and West of the city in the Danube basin in the first half of the nineteenth century (Krausmann 2012). After the great Danube regulation in Vienna in the 1870s, the supply of grain transported to the city on steamships increased sharply (Gierlinger et al. 2013). Cereals from distant regions such as Transylvania, roughly 650 km downstream of the city, were transported to Vienna (Winckler 1870). Like in Paris, in prerailroad times, slaughter animals came from regions further away than other foodstuff. In 1811, around 68 % of all cattle slaughtered in Vienna were driven to the city in large herds from the Hungarian plains (200–350 km distance), 28 % from Moravia (around 170 km distance). Only 4 % originated from the immediate surroundings of the city in Lower Austria (Fajkmaier 1912).

In Paris, daily per capita intake of food and feed in terms of nitrogen was more or less stable throughout the nineteenth century at around 24.1 gN/cap/day (Barles 2007a, Table 2). This was different in Vienna, where inflows of nitrogen decreased from around 24.3 gN/cap/day in the 1830s to 20.6 gN/cap/day in the 1880s. The total value for the 1830s is similar to that of Paris, but its composition was different.

The share of meat in total food inflows was rather high in Vienna, both in the 1830s and the 1880s. Sandgruber (1982)

Table 2 Average daily inflow of dietary nitrogen in Vienna and Paris in the nineteenth century given in gN/cap/day (data for Paris are from Barles 2007a)

	Paris Nineteenth century	Vienna 1830–1840	Vienna 1880–1890
Cereals	6.3	7.7	6.1
Meat	6.3	8.5	7.3
All other foodstuff	6	3.1	3.5
Feed	5.5	4.9	3.8
Total	24.1	24.3	20.6

came to a similar conclusion comparing meat consumption in the nineteenth century in several cities in present-day Germany and Austria. On the one hand, in Vienna, the wealthiest families of the monarchy were concentrated and thus could afford a meat rich diet. Nevertheless, in the second half of the nineteenth century, the working class with different dietary pattern than the upper class was growing. On the other hand, Vienna was situated close to the fertile and sparsely populated Hungarian plains, where an abundance of cattle was bred (Sandgruber 1982).

The fate of nitrogen after food and feed consumption was different in Vienna and Paris. Both cities had to cope with an increasing amount of urban excreta, river pollution and increasing sanitary nuisances (Barles and Lestel 2007; Gierlinger et al. 2013). Debates on how to deal with urban excreta and how to keep the urban waters clean were on the agenda in both cities. With advancements in the scientific understanding of plant nutrition hygienists, scientists and officials in Paris in the 1830s started to perceive nitrogen as a valuable agricultural resource (Barles and Lestel 2007). This led to the search for sources of nitrogen and the development of an organic and mineral fertiliser industry. With the introduction of the flush toilet and the increasing water consumption in the second half of the nineteenth century, a shift from dry fertiliser production to sewage farming took place. In the 1860s, first experiments with sewage farms were made in Paris. The concept quickly gained significance, and at the beginning of the twentieth century, more than 50 km² of sewage farm land existed in the surroundings of Paris (Barles 2007a). At the beginning of the twentieth century, a considerable part of the urban nitrogen inflow was returned to the land, as agriculturalists asked for. In 1913, around 40 % of the dietary nitrogen inflows in Paris were returned to agriculture via sewage farms, produced fertiliser or the spreading of horse manure and street sludge (Barles 2007a). In Vienna, the development was different. Projects for industrial fertiliser production from human manure and projects for the installation of sewage farms were not realised. Instead, the problem of river pollution and sanitary nuisances was tackled by reconstructing the sewage system and shifting discharge to a place outside residential area.

In Paris, organic loading of the river Seine was recognised as the main source of river degradation. Decomposition of organic matter by microorganisms reduces the oxygen content in the water, which may lead to lethal conditions for fish when there is too little oxygen in the water. In 1874, the hygienists Auguste-Charles Gérardin and Félix Boudet (cited in Barles and Lestel 2007) performed an oxygen content analyses on the Seine and found that the oxygen content fell from a natural level of around 8 to 9 square centimetre per litre measured upstream of Paris down to one square centimetre per litre in the city, which was too low to sustain any higher organisms. The organic pollution from Paris waste water disposal was so high that it affected river quality even 100 km downstream of Paris (Barles and Lestel 2007). The situation in Vienna was different. Mean discharge rate of the Danube in Vienna was at around 2000 m³/sec compared with roughly 250 m³/sec of the Seine in Paris. The discharge rate of the Seine was further subject to strong fluctuations and, in periods of low water, was as low as 35 m³/sec (Huxley and Lamy 1882; Barles 2007b). As mentioned, earlier contemporaries assumed that the self-purification capacity of the Danube was sufficient for absorbing large amounts of urban sewage. Brezina (1906) showed that the oxygen content of the Danube reached the same level it had before discharge already around 8 km downstream (see more in the Online Resource S4).

Summing up a combination of several factors influenced the differing choices on the disposal system in Vienna and Paris: Comparatively, easy discharge even before the introduction of the central sewer system due to the geomorphological situation in Vienna, little demand for fertiliser in the immediate surroundings of the city and a huge urban river that was perceived as being able to absorb the sewage of the entire population in Vienna without massive degradation of the water quality worked against the implementation of an efficient recycling system of urban organic wastes but supported the discharge into the waterscape. In Paris, the introduction of sewage farms in late nineteenth century helped reducing the massive organic pollution of the Seine. In Vienna, discharge into the small streams and rivers was brought to an end by either incorporating the small streams into the sewage network or by the installation of intercepting sewers along the larger streams. Instead of agricultural fields, the destination of sewage was the large river Danube.

Conclusions

In the nineteenth century, Vienna has been transformed into an industrial city. This process was characterised by urbanisation, massive population growth and a changing

relationship with its agricultural hinterland. Rapid urbanisation led to a concentration of large amounts of dietary nitrogen in a comparatively small area and required new ways of disposal. This had consequences for the regional nitrogen cycle. In the time period under investigation, withdrawal of nitrogen from urban hinterlands for the supply of Vienna with food and feed multiplied fivefold. At the same time, the amount of nitrogen disposed of in urban waters increased sevenfold. The study compared dietary nitrogen flows in Vienna and Paris. Both cities faced the same macro-processes such as industrialisation, urbanisation and the energy transition but still differences existed on the local scale. In both cases, the inflows of nitrogen increased sharply. The average daily inflow of nitrogen per capita was similar in nineteenth century Vienna and Paris, but the composition of the sources of the nitrogen differed considerably. The share of nitrogen deriving from meat consumption was much higher in Vienna than in Paris. Both cities had to deal with the disposal of a rapidly increasing amount of urban excreta. The sanitary question and debates on what would be the optimal disposal system took place in both cities. But urban authorities decided on different solutions. The decisions taken by urban actors on the disposal system had differing impacts on the urban waterscapes. In Vienna, a centralised waterborne sewage system was built, discharging almost the entire sewage of the city into the river Danube. The specific geomorphological situation of Vienna lying on the outskirts of the Alps and being intersected by many small streams discharging into a huge river with relatively high velocity supported that decision. Parisians on the other hand decided to build sewage farms, where part of the sewage was reused in agricultural production. This was a way of reducing organic pollution of the river Seine. Due to its sheer size, river pollution was not such an issue for the Danube in Vienna. The discharge rate of the Danube which was tenfold larger than that of the Seine allowed to absorb a much larger amount of organic material.

In present-day global change discourse, human interferences with global nitrogen cycles are presented as one of the major sustainability challenges. One cause of the imbalance of global nitrogen cycles lies in the spatial disintegration of agricultural production and consumption triggered by the process of urbanisation. The spatial disintegration of production and consumption is responsible for nitrogen drainage from the agricultural hinterland to urban centres where it causes problems of disposal of urban excreta. The case of Vienna in the nineteenth century served as an example for demonstrating dynamics of urban nitrogen flows. The comparison with Paris showed that even if the same macroprocesses took place differences in nitrogen-related input and output flows existed and different solutions to output-related problems were adopted.

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