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UNCNET

Urban nitrogen cycles: new economy thinking to master the challenges of climate change

D6/3: Extrapolation of methods on waste to human dwellings/constructions and circular economy concepts

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Dissemination Level		
PU	Public	☒
PP	Restricted to other programme participants (including funding agencies)	☐
RE	Restricted to a group specified by the consortium (including funding agencies)	☐
CO	Confidential, only for members of the consortium (including funding agencies)	☐

1. Executive Summary

Private households and human dwellings constitute an own pool in the urban nitrogen budgets. Due to the lack of economic activities in this pool, the statistical database needed to provide robust information is fairly poor. Hence N flows need to be provided as balances from other pools, with the waste pool being intrinsically connected, serving as a key outlet to households, again based on limited information. Here we present a coherent methodology to describe the "households" pool and apply it to the urban situations of Vienna and Zielona Góra as examples. This allows to identify the challenges associated with this pool, and to quantify its contribution. As people tend to be the endpoints of the agro-food chain, while at the same time being final consumer of relevant industrial products, its central position in the overall nitrogen budget (not only, but also in the urban scale) becomes apparent. In the urban situation, the closest links on the input side is the industry pool, while the closest links on the output side are the waste and wastewater pools. For urban surroundings, ties to animal systems and to urban agriculture tend to be more pronounced. Households also play a primary role in attempt of recycling of material containing nitrogen. This starts with food waste, but also encompasses other materials rich in nitrogen (fibers, dyes, plastics, wastewater). Thus, quantifying the recycling rate and recycling potentials is a core application for the household pool within an urban nitrogen budget.

2. Objectives:

Objective of this deliverable was the development of an approach that enables the calculation of flows in and out of the household pool and presenting a solution to the problem of limited data. The interlinkage between the households and waste pool were investigated more closely to help develop these solutions as well as identifying potentials for recycling and emission reductions.

3. Activities:

- Development of an approach to calculate all flows to and from the household pool
- Investigating recycling potentials linked to the household pool

4. Results:

- A framework of an approach to estimate data on flows into the household pool where no information is available
- An estimate of recycling potentials for Vienna and Zielona Gora

5. Milestones achieved:

M3 – Workable guidance principles to create N budgets available

6. Deviations and reasons:

Delay due to Corona crisis.

7. Publications:

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8. Meetings:

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9. List of Documents/Annexes:

Annex I: Urban Nitrogen Budgets: methods description for the “households” pool

10. Bibliography

ANNEX I

Urban Nitrogen Budgets:

Concepts to describe N flows in the “households” pool

Introduction

This paper covers the treatment of N budgets in an anthropogenic pool that is most distant to economic activity, the “household” pool. In national budgets classified as “Humans and settlements” (conceding slightly different definitions and system boundaries), handling of materials and information on processes in this pool is generally ill-described and data quality is poor, if any is available. Flow data mostly are obtained from the outside, from economic activities and material exchanges with households, and from the biophysical human requirements. A strong interchange exists with the waste sector. Hence the intersection (and common treatment) of households and waste determines the logics of this deliverable. The need of using balance data in several instances (e.g. when calculating N inflows from industry) prevents quantification of pool changes (accumulation of materials), which had been proposed on a national level (Pierer et al., 2015).

Method

Here we describe general approach, methodology, and challenges regarding establishing the household pool flows in close consideration of the flows of the waste pool. The practical implementation in the respective cities is described with the respective urban N budgets.

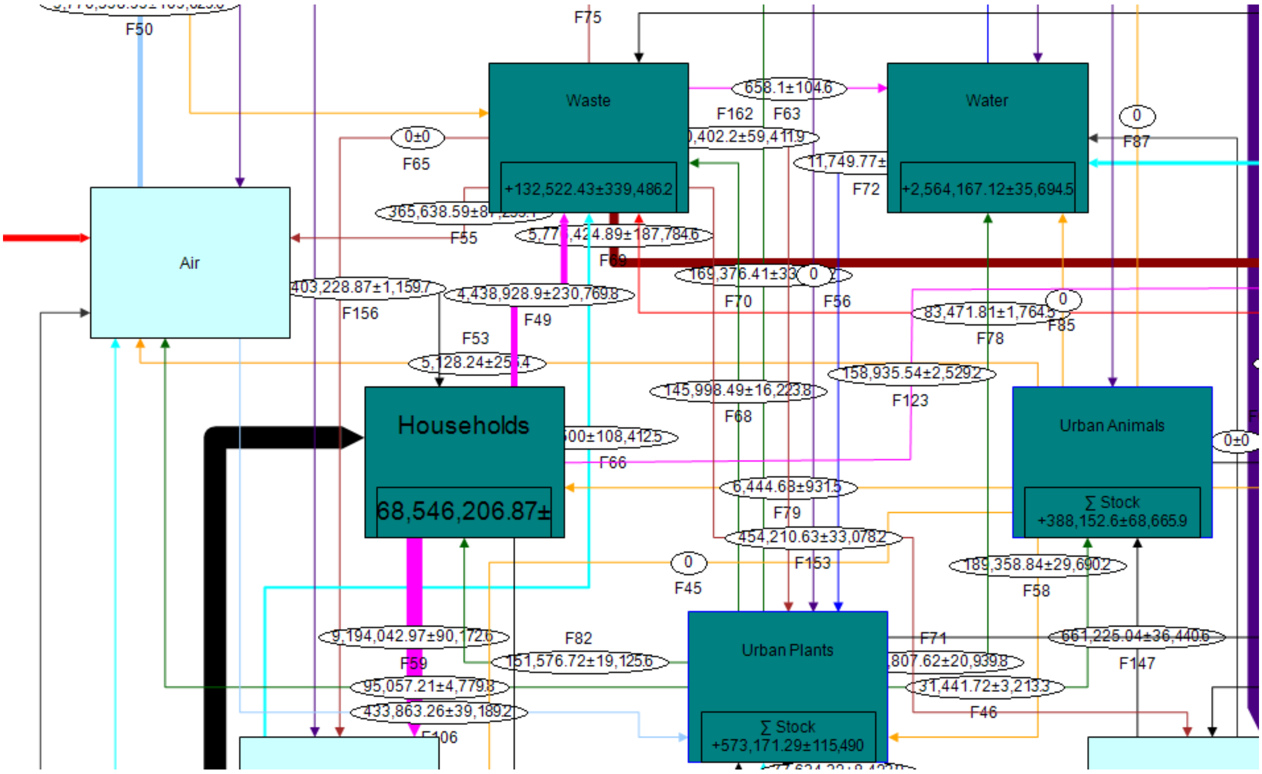

Figure 1: “Households” pool in Vienna core area

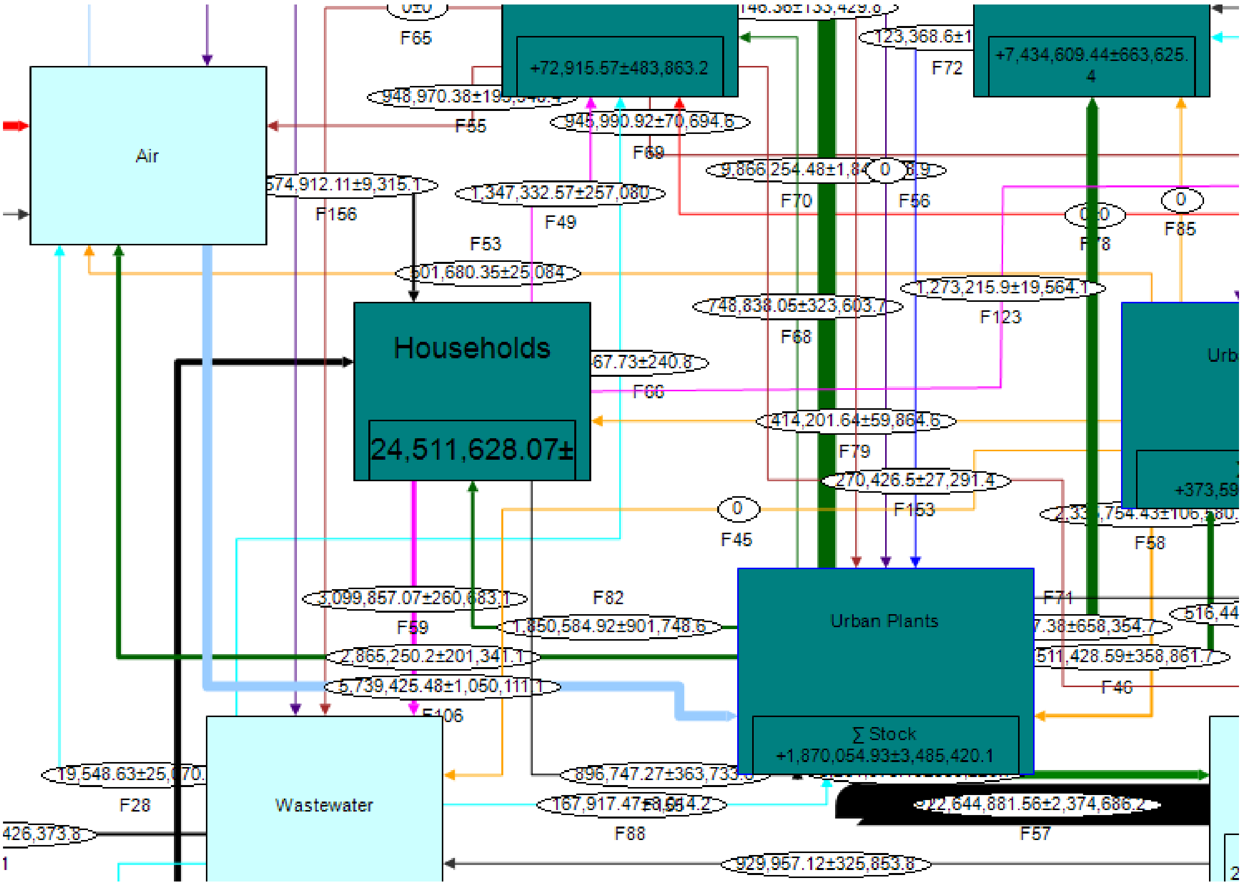

Figure 2: "Households" pool in Vienna surrounding area

Major inflows to the household pool are coming from industry (food and products such as textiles, furniture, fuels, etc.) or agricultural land (plant-based food), horticulture (plant-based food) and urban livestock (meat/milk) depending on the self-sufficiency of the test area. There is a minor N flow from air to household pools representing N deposition on built-up areas. Major outflows from the household pool are directed to the waste and wastewater pool as well as the urban green pool. The flow to the urban green pool represents home composting in gardens. A minor flow is directed to the combustion pool representing residential heating.

However, depending on the structure of the test area, the significance of specific flows changes. Flows from agricultural land and urban livestock are usually smaller in the core urban areas than in their surround, with the European core urban areas showing no flow from urban livestock to households as no livestock is kept. The flow to urban greens, only exists in the Vienna surrounding area (and in Klagenfurt-Villach in Austria, for which data also was made available) as home composting is not a common practice in Poland or China. In Shijiazhuang and Beijing, there is a flow from households to urban agricultural land representing human manure recycling, a practice that does not exist in any other test areas.

As information on flows into the household pool is often incomplete, a balancing approach needs to be applied. This derives from the understanding that the respective other endpoints of flows are much better statistically characterized, constituting economic activities for which detailed data typically is available. For Vienna and its surrounding, for example, several balancing approaches were fused to arrive at an estimate of minimum N import needed to meet the population's demands.

To estimate food demand, data on crop and livestock product consumption per capita (differentiating between different meat products – beef, mutton, etc., and milk, cheese, eggs etc. – and different crops such as fruit, vegetables, cereal crops etc.) was taken from food supply balance sheet of Statistik Austria (2021). This dataset also included information on losses on the household level, which need to be subtracted from consumption data to arrive at net consumption. This net consumption is needed to calculate the flow from households to wastewater. As data on losses was only available for Austria as a whole and not per capita, total loss data for Austria was converted to shares of production (e.g. 3% of production quantity of wheat is lost in the households).

An additional check for the data calculated from Statistik Austria (2021) for food consumption was made by comparing with the FAO food balance sheets for Austria (FAO, 2001). Converting the protein consumption found in the FAO food balance sheets to N gives a per capita N consumption of 6.25 kg per year, which is quite similar to the 6.13 kg per year calculated from Statistik Austria (2021).

Flows can also be derived from the production side, e.g. agricultural land and horticultural land where vegetables or fruit are grown. Quantifying inputs on the consumer side, however, requires accounting for the occurring losses. We use the factors taken from Winiwarter & EPNB (2016) to quantify losses specific for crop or meat type during production (field or stable) and in the distribution network (transport and supermarkets). Losses are subtracted from production to arrive at the net supply.

Total consumption per capita (without the subtraction of losses) was then compared to total supply per crop and meat type to calculate the total population demand. Import requirements or export potential then is derived as the difference of production and consumption.

To quantify the flow of N in other products from industry to the household pool, we assumed that it must match the flow from household to waste, subtracting organic waste (the organic waste fraction would be part of the agro-food chain, to be found in the stream of agricultural products to households). This calculation only gives a minimum of the consumption of other products as it neglects the accumulation of goods in households (stock change). On a country scale for Austria, Pierer et al. (2015) have found that such accumulation explains observed differences in the Household pool.

For Zielona Gora and its surrounding, the same approach was taken. Food demand was determined based on the average consumption of protein in animal and plant products. In a first try, food demand was calculated on the basis of Polish statistical data available for 2015 from the Central Statistical Office (GUS). However, when compared to the amounts of N in wastewater and food waste produced by residents, this approach seemed to underestimate actual food consumption. Therefore, eventually, EUROSTAT/FAOSTAT data for Poland was used to calculate the demand of plant-based and livestock products. This demand was then again used to calculate the amount of N in food that needs to be imported. Additional import needs from industry to the household pool were determined based on operational data on the amount of waste produced by residents in 2015, taking into account the residual waste stream and selective collection excluding kitchen and garden waste. In addition, the amount of nitrogen entering the household pool in fuel was taken into account. However, fuel enters the household pool and moves on to the combustion pool, remaining unchanged in magnitude. The nitrogen content of food in relation to the flow from industry to household had the highest share with 52%, while other industrial products, calculated from the waste balance, made up 38% of the flow and fuels accounted for 9%. Quantities of flows are presented in Table 1.

Table 1 Quantities of N flows relevant for the Household pool (Vienna and Zielona Góra)

	N intake plant-based	N intake meat-based	N in from industry	N production plant-based	N production meat-based	N losses (food waste - consumption)
	All in kgN per inhabitant					
Vienna	2.83	2.94	7.89	0.08	0	0.85
Vienna Surrounding	2.83	2.94	7.13	2.83	0.63	0.85
Zielona Góra	3.07	3.50	12.38	0.20	0	
Zielona Góra Surrounding	3.07	3.50	9.22	2.26	2.21	

To calculate household stocks that remain in the household pool permanently, for Austria, information from Lampert et al. (1996) was taken and, where possible, updated to better reflect the current situation. As can be seen in Table 2, home decoration and furniture constitute the biggest N stock due to the high N content assigned to these items. It should be noted that authors used estimates for the Swiss population, as no date on quantities of stored home decoration/furniture or stored food per capita was available for Austria. Data on textiles was taken from Greenpeace (2019), who stated that the average inhabitant between 14-69 years of age of Vienna keeps 86 pieces of clothing in stock while the average inhabitant between 14-69 years of age of Lower Austria (Vienna surrounding) keeps 94 pieces of clothing in stock.

Table 2 Household Stocks for Vienna and Vienna Surrounding

cap=inhabitant	Stock [kg/cap]	N content [kgN/kg]	Stock [kgN/cap]	Stock Vienna [kgN]	Stock Vienna Surrounding [kgN]
Electronics	163	0.02	3.26	5,960,000	2,131,000
Interior	516	0.065	33.54	61,315,000	21,926,000
Food	51	0.005	0.26	466,000	167,000
Textile Vienna	28	0.016	0.44	588,000	
Textile Vienna Surrounding	30	0.016	0.48		223,000
			Stock	68,329,000	24,224,000
			Standard error	22,719,000	8,054

Table 3 Household stocks for Zielona Gora and Zielona Gora Surrounding

cap=inhabitant	Stock [kg/cap]	N content [kgN/kg]	Stock [kgN/cap]	Stock Zielona Góra [kgN]	Stock Zielona Góra Surrounding [kgN]
Electronics	47	0.020	0.94	112,000	19,000
Interior	266	0.007	1.97	235,000	39,000
Food	91	0.016	1.45	173,000	29,000
Textile Zielona Góra	30	0.026	0.77	92,000	15,000
			Stock	611,000	101,000
			Standard error	213,000	35,000

In Zielona Gora and its surrounding (Table 3), the amount of furniture and electronics and textiles was determined to estimate nitrogen accumulation through household stocks. The amount of electronics was determined on the basis of statistical data, while the amount of textiles was determined on the basis of the average annual amount of clothing purchases in Poland. The highest nitrogen accumulation in the household pool was associated with interior (38%), followed by food (28%), electronics (18%) and textiles (14%). Total nitrogen accumulation in relation to inflows was 40% and can be assessed as high. Such a high value may indicate that not all outflows have been characterized in this balance.

Results and Discussion

Comparing the main in- and outflows to and from the household pool per capita, shows discrepancies between the test areas (Table 4). Some differences are more prominent between the core area and the surrounding areas whereas other discrepancies show structural differences between the test areas. In all core areas, the flows from urban plants and livestock to household are lower than in the surrounding, reaching almost zero for livestock. As these flows are too small to meet the inhabitants' food demands, much has to be imported into the test areas. Therefore, most of N input to the household pool in the core area is food (see Figure 3 for Vienna). The situation can be quite different for the surrounding area. In the case of Vienna surrounding area, nitrogen contained in fuels (oil or wood) becomes a sizable fraction of N input. These fuels are mostly used for residential heating but would have much less relevance in the core city where district heating and gas are the much more prevalent heating technologies.

Structural differences between the test areas can be observed when looking at the flows from household to urban green (home composting of organic and green waste) and household to livestock (food residues used as feed) and household to agricultural land (use of human excreta as fertilizers). Home composting is a common practice only in the Vienna surrounding area whereas feeding food residues to livestock and using human excreta as fertilizer is considered a common practice only in the two Chinese test areas, the latter being significantly more prominent in Shijiazhuang than in Beijing. The practice of using human excreta directly as fertilizer leads to a decrease of the flow from households to wastewater. However, adding up all flows gives very similar results as per-capita flows from household to wastewater for all test areas. The flow from household to waste, on the other hand, is very low in the Chinese test areas compared to the European test areas.

Table 4 Main in- and outflows to and from the household pool per capita for each test area

	Vienna	Vienna surrounding	Zielona Gora	Zielona Gora surrounding	Shijiazhuang	Shijiazhuang surrounding	Beijing	Beijing surrounding
	kgN/cap	kgN/cap	kgN/cap	kgN/cap	kgN/cap	kgN/cap	kgN/cap	kgN/cap
Livestock to household	0.00	0.63	-	1.56	0.15	0.36	0.00	0.80
Industry to household	7.89	7.13	23.51	25.39	3.50	1.50	5.60	5.10
Urban plants to household	0.08	2.83	0.21	1.60	1.09	12.48	0.15	1.10
Household to urban green	-	1.37	-	-				
Household to waste	2.43	2.06	3.07	-	0.47	0.33	1.42	1.42
Household to combustion	0.09	1.95	15.07	19.84	0.10	0.21	3.21	3.07
Household to wastewater	5.46	5.21	4.99	-	1.61	0.16	4.27	5.54
Household to agricultural land					2.89	4.96	0.43	0.43
Household to livestock					0.05	0.38	0.05	0.05

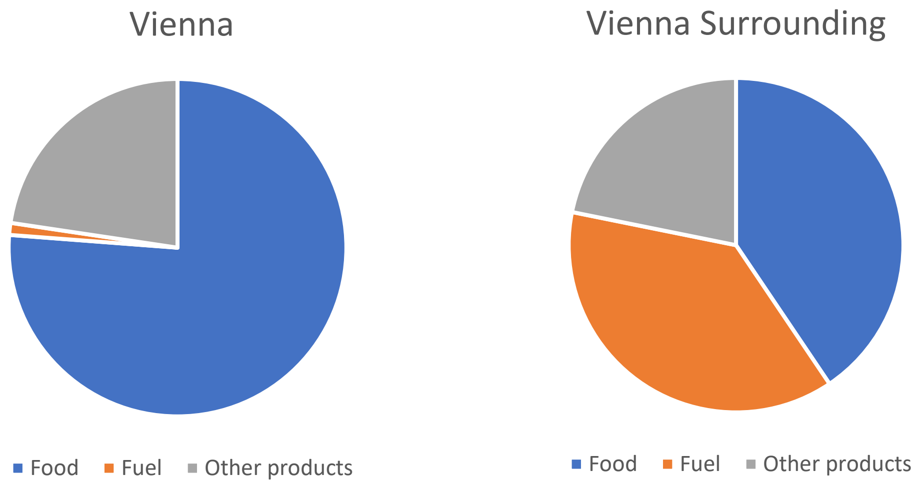

Figure 3 N input to household pool for Vienna and its surrounding area

Reduction and Recycling

Due to its centrality and close links to pools with high emissions to air and water (e.g agricultural land), the household pool can offer a great opportunity to enhance recycling with the most central elements being flows from household to waste and wastewater.

Waste

In Austria, a high percentage of waste is already being recycled (83% of paper, 84% of glass, 86% of metals). However, plastic recycling still needs improvement as only 25% were recycled in 2019 (BMK, 2021). Apart from increasing recycling rates for plastic waste, another potential lies in the fraction of organic waste (37% of total mass in Vienna and 12% in the Vienna surrounding) discarded as residual waste. If this fraction would be separated and composted, it could replace all synthetic fertilizer use in Vienna. However, as this fraction is small in the Vienna surrounding area and agricultural production is large, only 0.2% of synthetic fertilizer N could be replaced by recycling organic waste to agricultural land.

Legal obligations for the management of municipal waste (household waste and similar waste) are defined in the EU Waste Framework Directive. Such obligations include the goal of reusing/recycling

50% of municipal waste by 2030 (Article 11(2)(a)). However, in Zielona Góra and Poland, achieving 50% in practice will be very difficult due to the high losses from the treatment of individual waste fractions before recycling. Specifically, collection rates need to be much higher than the reusing/recycling rates to be achieved, as waste needs to be cleaned to remove contaminants and non-recyclable waste. Therefore, more of each type of waste needs to be collected than the required recycling levels in order to achieve the required recycling levels after cleaning at the sorting plant and taking into account material losses during treatment processes (the values of these losses are 1-50%). The total mass of waste streams that must be collected separately to ensure meeting the required recycling levels for 2025 and 2030 are very high, at 64.9% and 70.5% of the total mass of generated waste, respectively. Residual waste mass was 79.2% of the total mass of waste generated in 2015, and in 2020, 2025 and 2030 it is projected to be 52.7%, 35.1% and 29.5%, respectively. Separating the amounts of waste for recycling from residual mixed waste that are needed to meet the EU target is impossible. The quality of this waste will not allow it to be recycled, especially in the case of bio-waste, paper and cardboard. To meet the requirements, it is anticipated that increased recovery of bio-waste will be required.

In Zielona Gora itself, there is no recycling. The compost generated from selectively collected bio-waste, as well as the waste collected at the source and at Selective Municipal Waste Collection Points (PSZOK) facilities is recycled outside of Zielona Góra. However, this situation is slowly changing, an example being the establishment of a Point of Search (PS) in which waste is turned into needed items that will gain a second life. The PS is a point where items, unwanted by the previous owner, such as furniture, car seats, small electronics, or books, can be passed on to another person who can make use of it. There is also a board that will feature announcements from Zielona Góra residents who have a sofa, washing machine or lawnmower to donate. Additionally, Zielona Gora joined the National Electric Garbage Project in 2022. Twenty-two dedicated red containers have appeared in the city in convenient locations for residents. The red electric garbage bin is not only a convenient solution, but also an ecological one, as it allows free collection of waste for recycling.

Wastewater

Wastewater treatment plays a big role in the core areas. While the biggest flow related to this process (N_2 to air) cannot easily be reduced or converted in the current system, the flow from wastewater to waste and combustion could be redirected to increase nitrogen use efficiency within the test areas and beyond. In Vienna, all sewage sludge is being burnt with current discussions on making use of this resource focus only on Phosphorus, neglecting Nr recycling. The re-use of sewage sludge, which makes up over 30% of total waste could be seen as a potential to reduce emissions from synthetic fertilizer production when used as a substitute. It is estimated that around one ton of CO_2 is produced for every ton of NH_3 in the natural gas-powered Haber-Bosch process (common practice in at least 90% of western European countries: UBA, n.d.). For Vienna this would result in a reduction potential of 1-2kt CO_2 based on the assumption that 88% of sewage sludge are composted and around 50% of this compost can be used on agricultural fields (mimicking the current situation in the Vienna surrounding area). It would also be enough to substitute the total use of mineral fertilizer in Vienna with 2/3 of the compost then still available for export. However, this substitution may also cause increased ammonia emissions.

In Zielona Gora, sewage sludge is treated for application to agricultural land before being exported outside the city borders and recycled to agricultural fields. Sewage sludge in the treatment plant is subjected to aerobic mineralization or fermentation and then hygienised with lime. Sewage sludge processed in this way, will fulfill the legal requirements for heavy metals and parasites content and can thus be used on land.

Direct use of human excreta as manure in agricultural practices would be another option to increase Nr recycling of wastewater further. It has a long-standing and geographically varied history (Ferguson, 2014; Svirejeva-Hopkins et al., 2011). In South-East Asia and China specifically, human excreta derived fertilizer (HEDF) has withstood the era of chemically synthesized fertilizers and remains widely used (Liu et al., 2014). Although such practices were still adopted in some of the European territories until the last century, they have now been fully replaced by modern wastewater treatment plants, mainly due to newly-made nutrient availability (fossil phosphates, Haber-Bosch process, potash mines) and increased urban population (Esculier & Barles, 2019; Svirejeva-Hopkins et al., 2011).

If comprehensive guidelines on the adequate use of human excreta in agriculture now allow reducing the risk of pathogen contamination and enhancing nutrient recovery (Jönsson, 2004), social acceptance and higher ammonia volatilization than compared to Wastewater Treatment Plants (WWTP) remain obstacles to its technological expansion. (Moya et al., 2019; Spångberg et al., 2014)

However, research towards re-introducing direct use of human excreta is ongoing, identifying different options to do so. One option to directly recycle human urine is ecological sanitation. In an ecological sanitation – or ecosan – field, the use of human urine as fertilizer for crop production is additionally being investigated to close nutrient loops. Containing a high share of N (90%), P (50-65%), and K (50-80%) of households blackwater, as well as much fewer enteric microorganisms and a reduced risk to human health in comparison to feces, urine offers a promising alternative and/or complement to HEDF and conventional WWTP. (Hilton et al., 2021; Rose et al., 2015) Specifically, urine diversion and source separation, whether that is through novel decentralized systems (Kavvada et al., 2017) or nutrient recovery on-site within the individual toilets (Wald, 2022) are key aspects of new design concepts (Randall & Naidoo, 2018). Among other uses of urine along an enhanced NRR, struvite precipitation in fluidized bed reactors with P and K recovery (Wilsenach et al., 2007), use of microbial fuel cells (MFCs) to generate electricity (You et al., 2016) or NH_3 recovery following urea hydrolysis through electrochemical stripping (Tarpeh et al., 2018) or ion-exchange (Tarpeh et al., 2017) constitute recent noteworthy technological advances.

Considering a N urinary excretion rate of 4 kg per capita and year (Jönsson, 2004; Rose et al., 2015), the sole N recovery from urine as fertilizer using one of the above technologies would fully replace – excluding N losses of the respective recovery systems – the N mineral fertilizer use in Zielona Gora core and surrounding areas after redistribution of the N surplus in the core to the surrounding (see Table 5 below). Similarly, such recovery would fully replace the N mineral fertilizer requirements in Vienna core area and about 42% of the N mineral fertilizer need in the surrounding area following N surplus redistribution.

Table 5 – Gross estimates of recycled amounts of N from urine in Vienna and Zielona Gora (kt N.year-1) and their percentages compared to mineral fertilizer requirements before and after N surplus redistribution. Legend: VIE = Vienna; VIE+ = Vienna surrounding; ZG = Zielona Gora; ZG+ = Zielona Gora surrounding.

	VIE	VIE+	ZG	ZG+
N potential (kt N.year^{-1})	7.31	2.61	0.44	0.11
% Mineral fertilizer use	1828%	12%	1426%	26%
% Mineral fertilizer use after redistribution	100%	42%	100%	124%

Air pollution
Another reduction potential lies in private transport as this sector is responsible for over 30% of emissions from combustion processes. Reducing these emissions by e.g. promoting public transport and switching from combustion to electric engines is all planned according to the city of Vienna (Stadt Wien, 2022).

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Appendix: Flows in connection with household pool

(from: UNCNET – Brief description of flows and pools)

HOUSEHOLDS: This pool represents the households of the inhabitants of the respective study area and contains a stock that represents the N content of all products stored within the households (e.g. clothes, furniture, etc).

Inflows

Inflow connections to the households pool currently include those from the AIR, AGRICULTURAL LAND, HORTICULTURE, LIVESTOCK and INDUSTRY pools:

- **FLOW 156: AIR TO HOUSEHOLD:** This flow accounts for N deposition on urban (built-up) areas.
- **FLOW 109: AGRICULTURAL LAND TO HOUSEHOLDS:** This flow includes N in harvested crops used as food for households. For Vienna, the computed flow represents the total amount of harvested crops used as food. For Vienna surrounding area, the computed flow only represents what is being consumed in the test area by the households as more is produced in practice.
- **FLOW 115: HORTICULTURE TO HOUSEHOLDS:** This flow includes N in flowers or horticultural fruits/vegetables that are assumed to go to households. For Vienna, a fraction going to urban greens is subtracted.
- **FLOW 142: LIVESTOCK TO HOUSEHOLDS:** This flow includes N contained in livestock products (meat, eggs, milk, fancy meat etc.) consumed by the inhabitants of the respective region. For Vienna and its surrounding it is derived from food demand of population (average food intake).
- **FLOW 52: INDUSTRY TO HOUSEHOLD:** This flow accounts for N contained in industrial products going to households. These industrial products also include commercial ones, such as those found in small retailers or supermarkets. For Vienna and its surrounding this flow was calculated from balancing input with output, taking into account food demand. If available, more detailed statistics on household consumption are a better option.

Outflows

Outflow connections from the households pool currently include those towards the WASTEWATER, WASTE, URBAN GREEN and COMBUSTION pools:

- **FLOW 59: HOUSEHOLD TO WASTEWATER:** This flow accounts for N discharged by the population (e.g. excretion, household chemicals) into domestic wastewater.
- **FLOW 49: HOUSEHOLD TO WASTE:** This flow accounts for N related to residential waste only. All kinds of waste are taken into account. Hence, the waste composition is needed to properly assess the overall quantity of transported nitrogen.
- **FLOW 155: HOUSEHOLDS TO URBAN GREEN:** This flow represents N contained in household compost ending in urban greens (mostly private gardens).
- **FLOW 123: HOUSEHOLDS TO COMBUSTION:** This flow encompasses all N (NO_x, NO_2, NH_3 and N_2O) in fuels used by the residential sector (e.g. fuel wood, petrol, diesel, biofuels).