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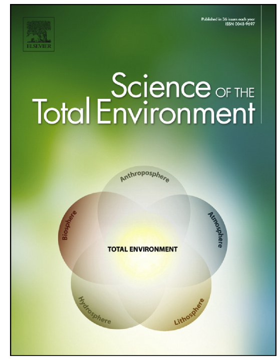

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The fate of nitrogen in the urban area – the case of Zielona Góra, Poland

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Abstract

The anthropogenic change of the nitrogen (N) cycle is strongly triggered by urban demand (such as food and meat consumption, energy demand and transport). As a consequence of high population density, impacts on human health through water and air pollution also concentrate on a city environment. Thus, an urban perspective on a predominantly rural pollution becomes relevant. Urban N budgets may be considered less intrinsically connected, so that separation of an agri-food chain and an industry-combustion chain is warranted. Results have been obtained for Zielona Góra, Poland, a city of 140 000 inhabitants characterized by domestic and transport sources and forest-dominated surroundings. In addition to food imports in Zielona Gora amounting to about 30%, in the suburban area a significant share of N amounting to 41% is related to fertilizer imports. The remaining imports are in fuel, elctronics, textiles, plastics and paper.Most of the agri-food N (45 %) is denitrified in wastewater treatment. N associated with combustion (mainly NOx

emissions from vehicles) represents a much smaller share than N entering via the agri-food system, amounting to 22% of the total N imports. This overall picture is maintained also when specifically addressing the city center, with the exception of mineral fertilizer that plays a much smaller role, with just 7% of N imports to the city.

Keywords: Nitrogen, urban, environment, circularity, air pollution, water pollution, nitrogen recovery from waste, nitrogen recovery from wastewater

1. Introduction

Humans exploit between 20% and 40% of the Earth's potential net primary biological production for their own purpose (Imhoff et al., 2004). The human impact can be traced to the way land has been transformed following human needs and desires for food production, energy provision, transport or accommodation. This impact specifically is notable in urban areas. Cities, despite only constituting about 3% of the world's land area (Hooke et al., 2012), differ substantially from a natural environment, both on a regional and global scale. This also relates to pollution emitted to air, water and land, which, due to the high concentration of emitters (public and private transport, combustion in power and heating, industry, sewage and waste storage and treatment installations, urban and suburban agriculture) in a small area, greatly exceed the permissible values that are safe for the natural environment and human health (Anenberg et al., 2022, Gu et al., 2012).

The degree of urbanization differs between and within regions. In Europe, built-up area including all traffic infrastructure covers about 6% (OECD, 2020), a value that increases for highly urbanized countries and regions: e.g., for England it is 9% (Morton et al., 2011), for Germany 12% (Wessolek et al., 2009), and for the Italian province of Lombardy even 13% (Canedoli et al., 2020). The increase of built-up areas is mainly at the expense of agricultural land and natural meadows, and to a lesser extent vegetable gardens, orchards and pastures (Morton et al., 2011). The development of cities at the beginning of the 21st century consumed approximately 15,000 km^2 of agricultural land per year globally (Döös, 2002). Now this process has been considerably intensified, which will result in the loss of 1.8-2.4% of cultivated area by 2030, of which as much as 84% will concern the Asian and African continents (Seto et al., 2012; d'Amour et al., 2017). This development will increase the competition between the different uses of land, such as between built-up areas (residential, services and industrial) and those in agricultural use, forest and of great importance for the nature protection.The way land is used also affects the elemental cycles associated with the land, specifically the nitrogen cycle. The release of reactive nitrogen (Nr) into the environment is an important source of environmental hazards, with Nr referring to the sum of all nitrogen compounds except unreactive N_2 (Galloway et al., 2004). According to Suddick et al. (2013) human activities affect the global N cycle more strongly than the global carbon cycle. Exceeding nitrogen limits has serious consequences for human health, biodiversity, air and water quality (Sutton et al., 2011; Suddick et al., 2013, Steffen et al., 2015). Main emission sources of Nr are observed in agriculture, a consequence of Nr being a plant nutrient and an essential compound of fertilizers (Erisman et al., 2008). In urban areas, main sources of Nr are linked to combustion in power and heating, industry, and transport, as well as waste and sewage treatment (Fowler et al., 2013).

Nr moves easily through the atmosphere, finding its way from the air to water and soil, and to plants in numerous chemical forms (Pinder et al. 2012). The “nitrogen cascade” (Galloway et al., 2003) describes the interlinkages between Nr compounds in different environment constituents. Concepts have been developed to assess not only the individual fluxes, but the bundle of fluxes in a budgeting approach (Leip et al., 2011; UNECE, 2013). While first developed on a country scale, recent efforts have looked into an urban situation also (Winiwarter et al., 2020; Kaltenegger et al., 2023), assuming that a budgeting approach allows to establish the interlinkages between the individual flows and hence leads to improved guidance to resolve the resulting environmental problems.

This article takes advantage of the methods developed to build National Nitrogen Budgets (NNBs) (UNECE, 2013) and presents the nitrogen mass flows for the city of Zielona Góra in Poland. It analyzes the sources of Nr compounds entering the city and being released into the environment, identifying the release points. Particular attention is given to quantify and to analyze options to improve recovery, reuse and recycling of Nr in an urban setting, aiming for a more sustainable pattern of Nr use in Zielona Góra as well as in comparable Polish and European cities.

2. Research area

Zielona Góra is a city of about 140 000 inhabitants, located in the western part of Poland (51°56'N, 15°30'E). The town's history dates back to the beginning of the thirteenth century where the inhabitants' activities were focused on agriculture and crafts (Schmidt, 1922, 1928; Ribbeck, 1929; Garbacz, 2003; Czyżniewski, 2010). The evolution of the urban territory until the end of the 19th century was limited to an area which is called 'historic center' today. In the 1950s, the city began to develop dynamically, as a provincial capital and an industrial, economic and cultural center (Czyżniewski, 2010). After the political transformation of Poland in 1990, Zielona Góra lost its industrial character, becoming a town with mainly a tertiary economy. This indicates clear differences both in terms of the scale and the intensity of anthropogenic impacts on the environment (Greinert and Drozdek, 2015). Until the end of 2014, the city of Zielona Góra (here used as the core area, ZG-C) was surrounded by a rural self-government unit – the commune of Zielona Góra (the new district, ZG-ND, describing the surrounding area of the core city). From January 1, 2015, these two units have been merged, which resulted in a marked change in spatial and demographic statistics. The land area and population number of the urban area of Zielona Góra between 1950 and 2022 as well as the land use types in ZG-C and in ZG-ND are shown in the supplementary materials fig. S1, b and Table S1. The analysis of the spatial development of the city of Zielona Góra shows that its current borders include two different morphologies (ZG-C and ZG-ND), i.e. two distinct areas with different ways of land development, different development policies and intensity of function development. Such different areas, with different population density, urban structure and different functions, are characterized by different nitrogen emission values. Land use as a key element underlying anthropogenic activities and hence also Nr cycles is displayed in Fig. 1.

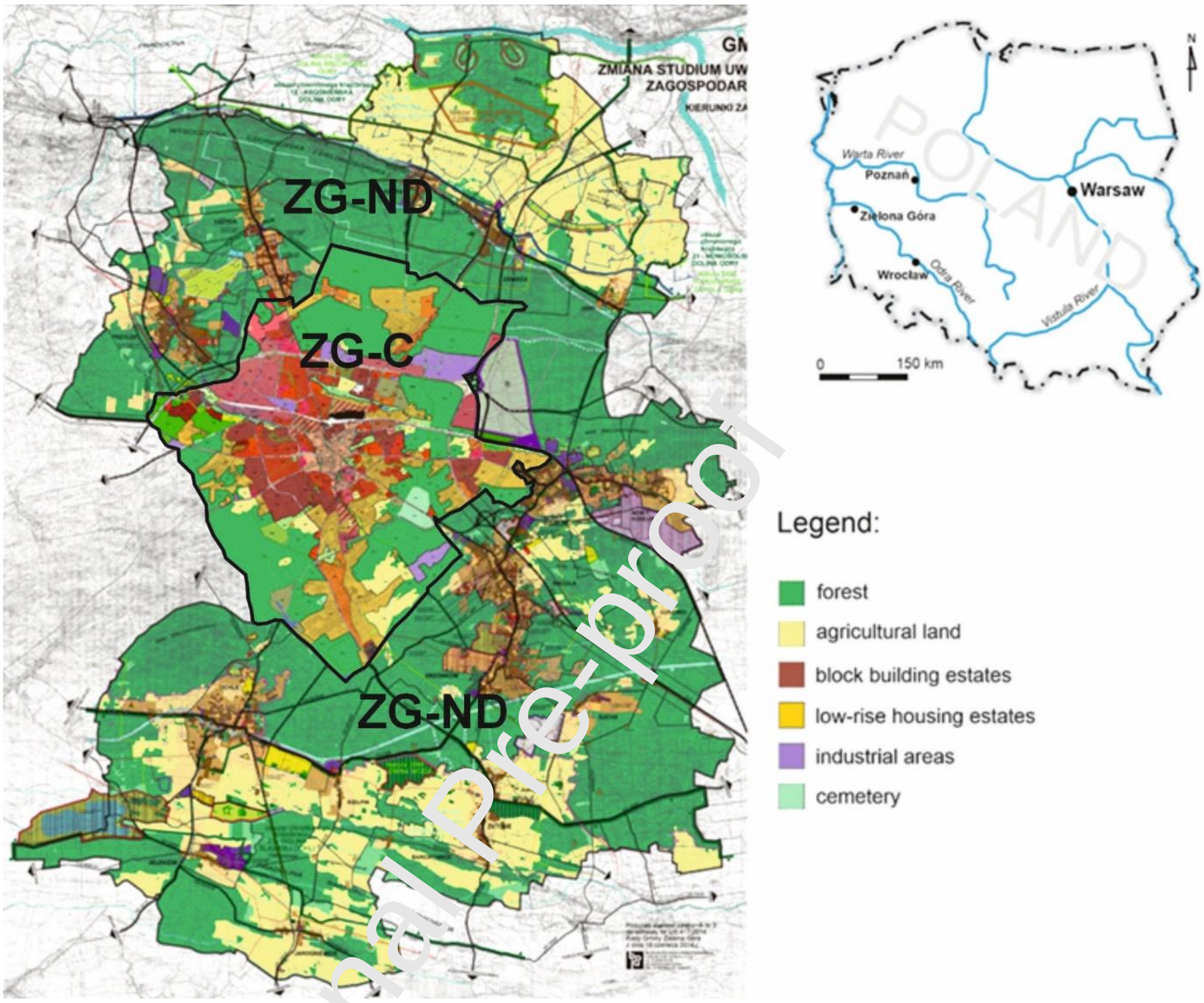


Fig. 1. Map of Zielona Góra urban area, divided to the ZG-C and ZG-ND, with the basic forms of land use (based on City of Zielona Góra, 2021)

3. Methods

3.1 Stock-flow model for Nr budgets

The analysis of Nr flows in the urban and suburban environment was performed using a model presenting mass flows and accumulation of Nr (Winiwarter et al., 2020). Based on the concept used in national N budgets (UNECE, 2013), pools have been defined that encompass Nr in the human sphere as well as in the environment, with the idea to quantify the exchange and the accumulation of Nr between and within these pools. Adapting the concept to urban systems, 10 pools have been identified within which nitrogen is transformed and accumulated (wastewater, waste, households, urban animals, urban plants, import/export, combustion, industry, air, water) (fig. 2.). Subsystems enabling a detailed description of flows have been added to two pools relating to urban agriculture (urban plants and urban animals). For the urban plants - pool, these comprise the horticulture sector, urban greens (urban land covered with grass, trees, shrubs, or other vegetation) and agricultural land; for urban animals, these are the - livestock and the pets sector (The Nr flows in the subsystems are presented in Figs. S2 and S3 in the supplementary materials). A description of the general approach used in the model has been given by Winiwarter et al. (2020), the model developed has been described in detail by Kaltenegger at al. (2023). The architecture of the Urban Nr budget pool is presented in the supplementary materials in Table S2.

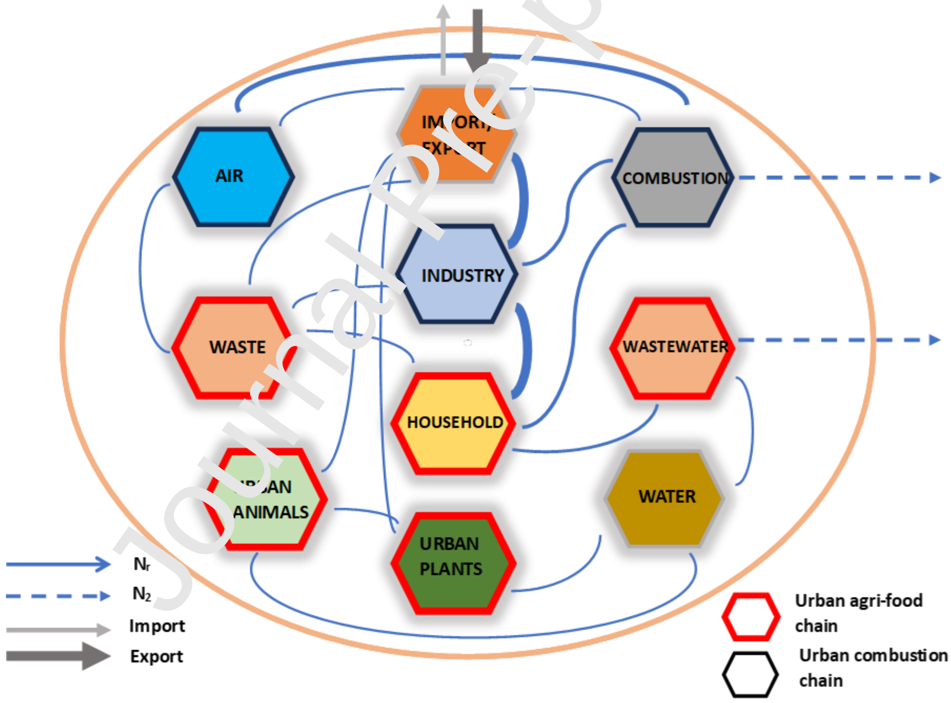


Fig. 2. General diagram of reactive nitrogen flows in the city

The software tool STAN (https://www.stan2web.net) was used to build this model showing the flows and accumulation of Nr while also enabling the evaluation of unknown flows using an integrated balancing approach (Cencic et al., 2008). In this nitrogen budget for the city of Zielona Góra, the flows contributing to the overall balance include imports, exports and stock changes.

For the calculation of Nr flows in the base year 2015 , data from the Regional Statistical Office in Zielona Góra and data coming directly from local units responsible for municipal economy was used. Additionally, data on wastewater was obtained from the Departments of Spatial Planning and Environmental Protection of the Municipal Office of Zielona Góra, the Department of Municipal Management of the City of Zielona Góra and the Wastewater Treatment Plant as well as the Waste Management Plant managed by the city Calculations for agricultural production, including animal husbandry, were made using data from IUNG in Puławy (Institute of Soil Science and Plant Cultivation, State Research Institute in Pulawy) and IMUZ in Falenty (Institute for Land Reclamation and Grassland Farming in Falenty) reflecting Polish specificity of livestock production (Bilski, 2008; Czyżyk et al., 2011). Data from IUNG reflecting livestock production in Poland and N content in manure from individual animal were used. The IMUZ data included atmospheric emissions from one animal, as well as from manure and from the soil after manure application, considering different land use form and cultivation techniques, as well as nitrogen leaching from sandy soil after application of N contained in fertilizers (mineral and organic). Volatilization of part of the nitrogen contained in manure in agricultural and storage areas during fertilization were also considered..

Data on pets in urban areas was obtained from the Annual Report of the Chief Veterinary Officer of the Republic of Poland on visits to animal shelters and general information on the number of dogs and cats in the EU by country (Sas, 2019). The annual reports from 2005-2017 include the numbers of dogs and cats in the country's shelters, including total, adopted and non-adopted animals, as a total number of horses in the country's shelters. The number of pets in households in Zielona Góra, as a number of free-living dogs and cats as well, was estimated using indices shown in statistics and documents of: CBOS (2003), Kantar (2017), BOZ (2023), and Chief Veterinary Inspectorate (2023). A total number of horses in 2015 was obtained directly from the equine facilities in: Zacisze, Racula (ZGC) and Raculka, Drzonków, Zabór, Przylep and some other small facilities (ZGND). Nitrogen content of substrates were used as presented in the National Nitrogen Budget Guidelines (Winiwarter and EPNB, 2016). In terms of impact on the environment and the characteristics of surface and ground waters, the results of measurements of the Regional Inspectorate for Environmental Protection were used (RIEP Reports, 1994-2017).

In addition, due to the fact that within the city borders of Zielona Góra there are units with two different morphologies (ZG-C and ZG-ND), i.e. two distinct areas with different land use, different development policies and intensity of functional development, nitrogen emission values were also presented for quarters characterized by a homogeneous internal urban structure and homogeneous development and land use, which made it possible to show individual nitrogen emissions from areas with different population density, urban structure and functions.

For this purpose, the city (ZG-C and ZG-ND) was divided into 102 quarters characterized by similarities in features such as: urban development (compact, detached, building height, standard), area functions (residential, service, production, agricultural production, cemeteries, parks), time of construction (before 1945, 1946-2022), population density, method of heat supply (solid fuel, gas, CHP, RES), method of development (built-up areas, parks, forests, arable fields, wasteland). Underlying data were derived (as presented in Table S3) from GIS data collected in the Urban Atlas and the database of the Zielona Gora Forestry Commission and GUS - Central Statistical Office - data for 2015 year (GUS, 2023). The number of people living in each quarter was determined based on data from the Central Statistical Office (city and village street database) with some quarters not inhabited (GUS, 2023). A list of each type and area of quarters is shown in Table S4 in the supplementary materials. The year of 2015 was taken as the base year for the calculation.

We also project changes in nitrogen flows for the urban agri-food chain, taking into account the new legal framework (Waste Framework Directive of 2018 (Directive 2018/851), Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse; Water Framework Directive 2000/60/EC) forcing changes in waste and wastewater management, which directly affects the Nr flows.

3.2. Scenario development in waste and wastewater sector

Waste Management Plant

Specific attention was given to waste streams, for which also scenarios of expected future Nr flows were developed. In Zielona Góra (both ZG-C and ZG-ND), mixed municipal waste (residual waste) and waste after selective collection, i.e., bio-waste, bulky waste, packaging waste (paper, metal, glass and plastic) and other recyclable waste components, are collected. The entire waste stream collected from this area is directed to the Waste Management Plant (ZZO) where, depending on the waste fraction, it is directed to:

- a regional installation for the mechanical and biological treatment (MBT) of mixed municipal waste with a capacity of 40,000 t · yr^{-1} mechanical part, biological part 23,100 t/year - mixed waste,
- composting plant for green waste and other biodegradable waste collected selectively with a capacity of 3,300 t · yr^{-1}– biowaste,
- sorting plant for selectively collected waste - waste after selective collection.

The actual and projected masses of waste streams directed to MBT for the period 2015 - 2030, together with the physical and chemical characteristics of selected components, are presented in Tables S6 and S7 included in the supplementary material. The basis for forecasting changes in the amount of municipal waste generated in Zielona Gora (ZG-C and ZG-ND) is the data contained in the databases of the Central Statistical Office for the year of 2018 (GUS, 2023), waste management plans (2002, 2006, 2014), reports of the Mayor of Zielona Góra (2016-2017) and data obtained from ZZO (2013 and 2015). The amount of municipal waste generated in year "t" (Q_t) was calculated from the following formula:

$$Q_t = NI_{2019} \cdot \left(1 + \frac{PGR}{100}\right)^{(t-2019)} \cdot q_t$$

Where:

NI_{2019} – number of inhabitants in 2019,

PGR - average population growth rate increasein the period 2015 - 2030; a value of 0.43% was adopted, which was determined based on the forecasts of the Central Statistical Office (for the year of 2012) (GUS, 2023), after adjusting the input data and updating the assumptions resulting from historical data for cities with 100,000 inhabitants for the years 2014-2020;

qt - waste generation rate per capita; the value of the indicator for Zielona Gora (ZG-C and ZG-ND) was 395 kg· C^{-1} ·year $^{-1}$ in 2015; for 2015-2019, the data comes from the ZZO, and the projection of the increase in the value of the index, was determined by assuming such a trend in its growth as the growth of average GDP income (gross domestic product per capita) for EU28 in 2013 - 2018.t – year of projection.

The material (morphological) composition of the generated municipal waste (qt) was determined on the basis of data from the ZZO. Changes in the morphological composition in the years 2020-2030 have been developed taking into account the observed trends resulting from changes in people's lifestyles, an increase in the level of prosperity and changes in regulations regarding the reduction or elimination of certain products (e.g. disposable plastic items). The implementation of circular economy, the growing environmental awareness, the implementation of anti-smog programs and changes in the area and ways of using green areas in cities and in individual gardens, as well as the development of housing construction, were also taken into account.

Wastewater treatment plant

The "Łącza" wastewater treatment plant (WWTP) in Zielona Góra was put into operation in December 1998.

Wastewater from ZG-C and ZG-ND is supplied to the treatment plant through an open channel equipped with damming structures forming five retention tanks. It is a mechanical and biological WWTP operating in a three-stage biological wastewater treatment system with biological dephosphatation, denitrification and nitrification. The receiver of treated sewage is the Łącza Canal, a left-bank tributary of the Zimna Woda watercourse. The average amount of sewage is 10,287 thousand m^3/year. The usage rate by residents of the communal sewage network is over 98% .

In the base year 2015 (198,087 PE (Population Equivalent)), the sewage sludge treatment system included thickening with conditioning, drying and incineration. As thermal treatment of sewage sludge was not economically justifiable due to the small amount of sewage sludge, it was not used continuously. In 2021, an installation for the methane fermentation of sewage sludge with biogas recovery was put into operation. A major benefit of using digestion to process sewage sludge is the production of electricity and heat. In 2022, 1540 MWh was produced from biogas in the power unit, which is 30% of the coverage of the treatment plant's energy needs. At the same time, 61% coverage of heating demand in winter and 93% in summer was achieved.

No technological changes in the system are expected until 2030, hence the nitrogen cycle in WWTP will remain unchanged. The nitrogen balance in the WWTP was made based on the parameters and indicators listed in the supplementary materials (Table S10). Average population growth rate in the period 2020 – 2030 was assumed at a value of 0.43%, which was determined based on the forecasts of the Central Statistical Office (for the year of 2022) (GUS, 2023), after adjusting the input data and updating the assumptions resulting from historical data for cities with 100,000 inhabitants for the years 2014-2020. For the forecast in 2030 was established increase to 211,255 PE.

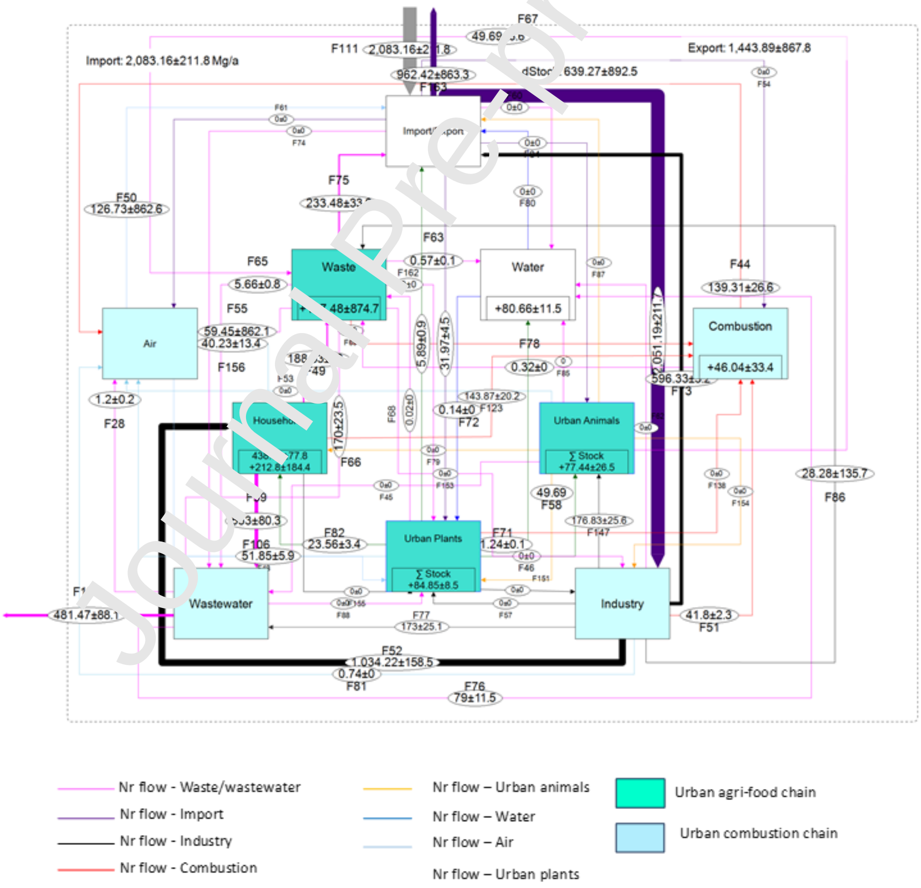
The dehydrated and sanitized sewage sludge is used outside the city for the cultivation of plants not intended for consumption and for the production of fodder as well as for land reclamation, including land for agricultural purposes

4. Results

4.1. Nitrogen flows in Zielona Góra urban area

Analyzing Nr flows in the urban area (ZG-C) and the peri-urban area (ZG-ND), it can be seen that the highest mass of Nr imported to the ZG-C was transformed as a result of human consumption, resulting in high emission of N_2 to the air from the denitrification process carried out by wastewater treatment plants, NOx emissions from combustion processes and NH_3 and to a small extent N_2O emissions from waste treatment installations. Some of the Nr imported to ZG-C was converted through industrial production and exported as a product (Fig. 3).

In the peri-urban area (ZG-ND), the largest share of Nr imported into the area was in mineral fertilizers and was transformed through agricultural production into commodities, some of which were exported (Fig. 3). Due to a higher level of local agricultural production, the ZG-ND area is more self-sufficient than the ZG-C areas in terms of plant and animal food. However, this area shows a higher accumulation of Nr in soil and water.



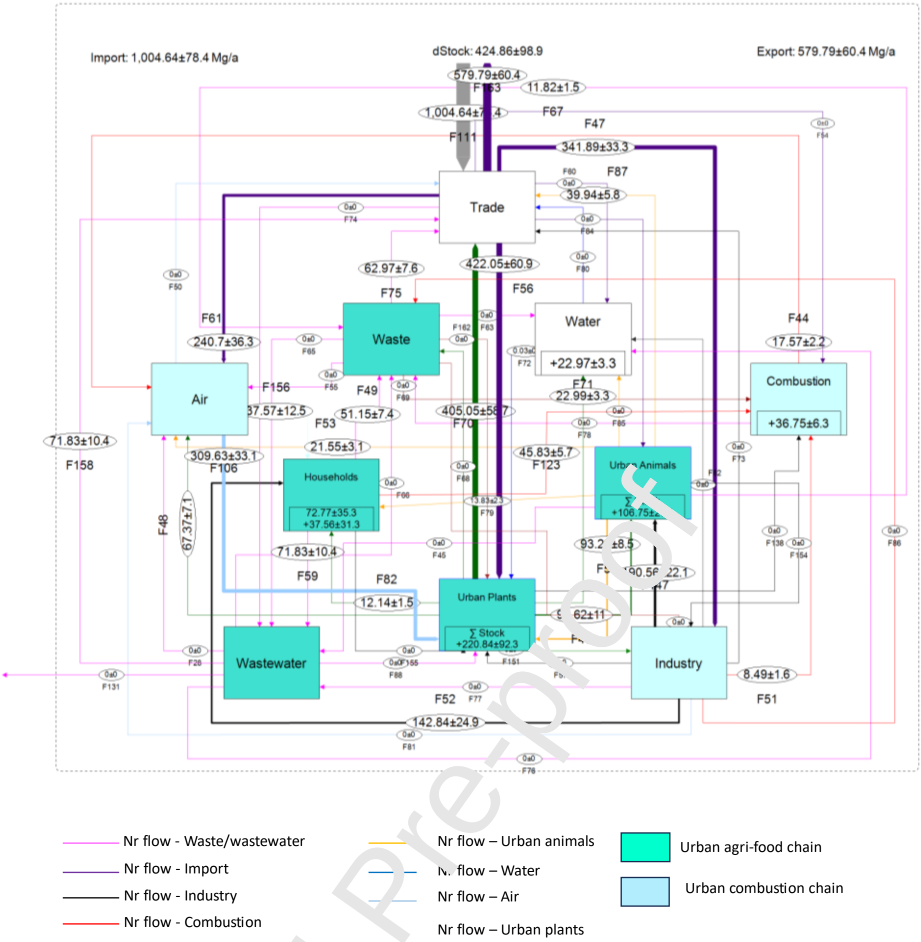


Fig. 3. Nitrogen flows (t N · yr^{-1}) in ZG-C- a. (top) and in ZG-ND - b. (bottom) for the year 2015

Separating Nr flows through cities into two systems: "S" - including urban agriculture, households, trade, wastewater and waste, and "urban combustion chain" - comprising industry, combustion and air (Winiwarter et al., 2020) it can be seen that largest Nr flows are found along the agri-food chain. In addition to food imports in Zielona Gora amounting to about 30%, in the suburban area (ZG-ND) a significant share of N amounting to 41% is related to fertilizer imports. The remaining imports are in fuel, elctronics, textiles, plastics and paper. . A higher share (45%) of the Nr imports to the agri-food sector is denitrified through wastewater treatment. Nr associated with combustion (mainly NO_x emissions from vehicles) accounts for a much smaller share, with 22% of total Nr import. The parameters and indicators for flow Nr in ZG-C and ZG-ND are shown in Table S5 presented in supplementary materials.

This overall picture is maintained also when specifically addressing the city center, with the exception of mineral fertilizer which plays a much smaller role. Considering the ZG-C and ZG-ND areas from the point of view of building types and land use based on the spatial structure of the 102 homogeneous quarters, it is possible to pollution sources in ZG-C and ZG-ND on the one hand, and areas potentially affected by the impact of reactive nitrogen on the other hand.

Nr imports to ZG-C and ZG-ND and N emissions to air are shown in Fig. 4a and 4b, respectively. The highest values of imported Nr are associated with the most densely populated quarters due to houses being - places of preparation and processing of food and other products imported or manufactured in ZG-C or ZG-ND, as well as places of fuel consumption, including individual systems for heating and hot water. High Nr values were also found in quarters with large areas of agricultural crops and high livestock density. Quarters with a predominance of forest areas, found in the immediate surrounding of ZG-C, were not found to import large amounts of nitrogen compounds.

The source of the greatest nitrogen emissions into the atmosphere (the most intense color in Fig. 4b) are the following quarters:

1) most densely populated;

2) as well as those in which the heating plant is located;

3) and quarters that are areas of intensive agricultural cultivation (volatilization of synthetic fertilizers) and livestock production;

4) and quarters with the highest density (area) of communication areas (expressways, transport junctions).

This is particularly visible in some of the quarters of ZG-ND.

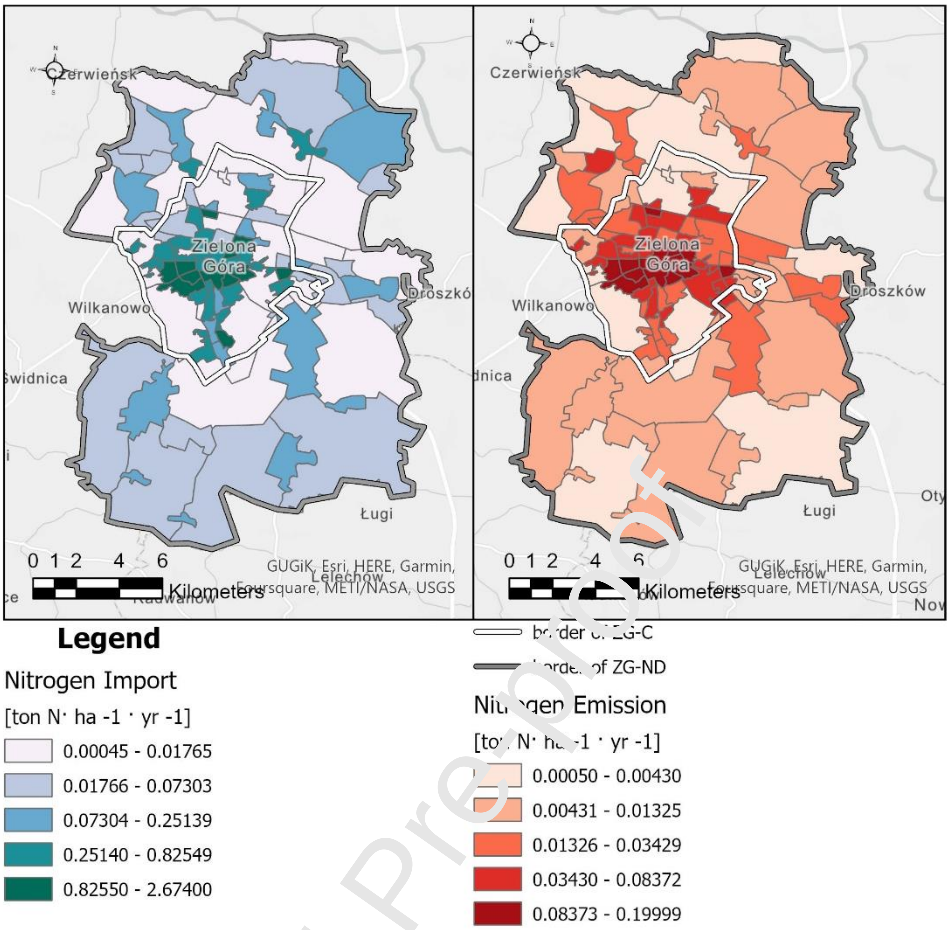


Fig 4. Nitrogen Import a. (left panel) and Nitrogen Emission b. (right panel) in ZG-C and ZG-ND

4.2. Land-use related Nr flows

In urban areas, agriculture is not expected to be of prime importance. Still in ZG-C, 8.1% of the area is arable land, considered to also include allotment gardens and home gardens, and 1.2% is permanent grassland.

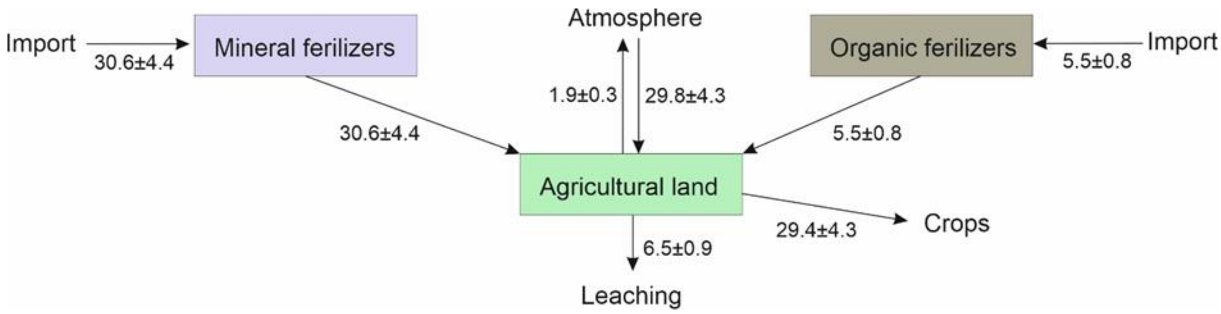
Agricultural land in the city has the status of land reserve for future development. Nevertheless, agricultural production is allowed to continue until the form of land use is changed. The temporary nature of the use is usually reflected in an extensive form of agricultural activities. In the first plan, this has been reflected in reduced use of pesticides and fertilizers.

In the ZG-C area, agricultural land is fertilized only with mineral fertilizers, excluding the possibility of using manure due to the immediate vicinity of built-up areas. The average use of nitrogen fertilizers in 2015 was 61.7 kgN·ha^{-1} and steadily decreased until 2019 to 55.4 kgN·ha^{-1}. Fertilization with other elements was also low during this period. These are typical rates for Poland, applied to very light – sandy soils in temporarily used agricultural fields. A slightly different situation characterizes the ZG-ND areas with a distinct agricultural character (Table S11), but also with high peri-urban construction pressure. Manure is allowed in the area, the application rate of which averaged 11.2 kgN·ha^{-1} in 2015. Part of the manure produced in the ZG-ND, in amounts equivalent to 5.5 kgN·ha^{-1}, was exported outside the ZG – to neighboring municipalities. Besides, the fields were fertilized with mineral fertilizer at the same rate as in the ZG-C area.

Extensive farming of livestock is also carried out in the ZG-ND area, mainly for the farmers' own needs and for local sale (including the area of neighboring communes). In 2015, livestock breeding covered 18 cattle per 100 ha of agricultural area (a total of 1,215 in ZG-ND) and 37 pigs per 100 ha (a total of 2,498 in ZG-ND). The exception was chicken production, which, apart from scattered individuals, included one farm. In total, in 2015, 65,000 animals were bred in the area of ZG-ND – this is 964 per 100 ha of agricultural area.

Nitrogen management associated with livestock production is largely related to the masses of manure produced. The mass of 139.7±36.1 tons N in manure is a subject of volatilization in breeding places (27.0±3.9 tons N), and in agricultural land (9.1 tons N, a part of total amount of 25.3±3.7 tons N volatilized from the AL). The 9.4 tons N were leached from soils fertilized with farmyard manure (a part of total amount of 89.0±12.9 tons N leached from the AL). The nitrogen in livestock fodder comes about 50% from the own production of forage crops in farms. The rest of demand is supplemented with imported concentrate feed in the form of ready-mixes.

a.



b.

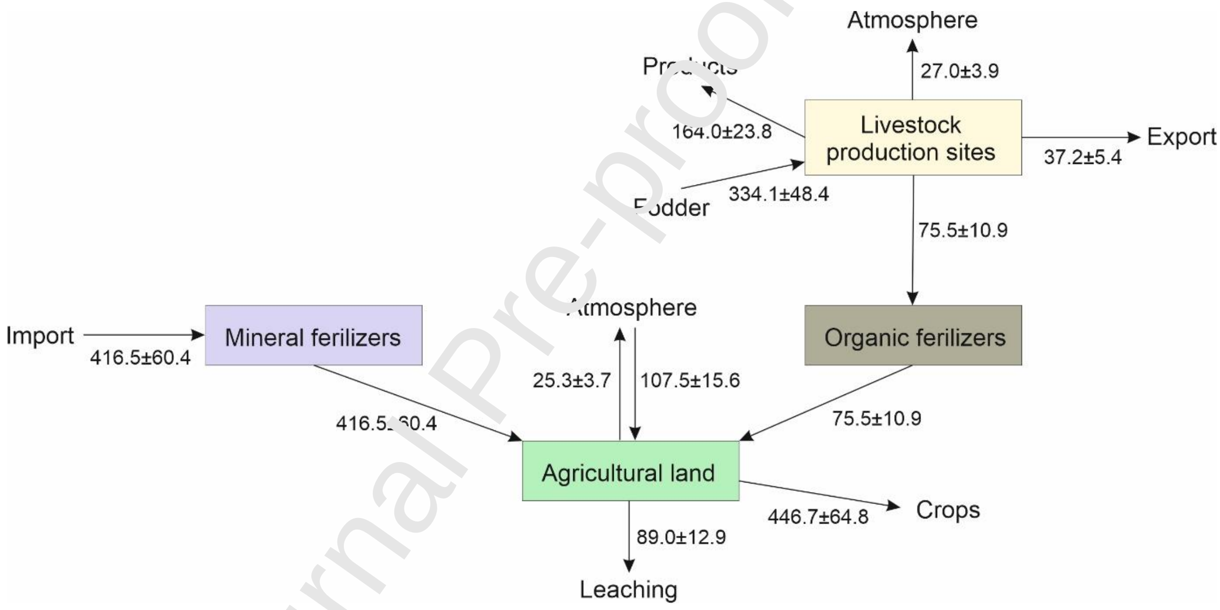
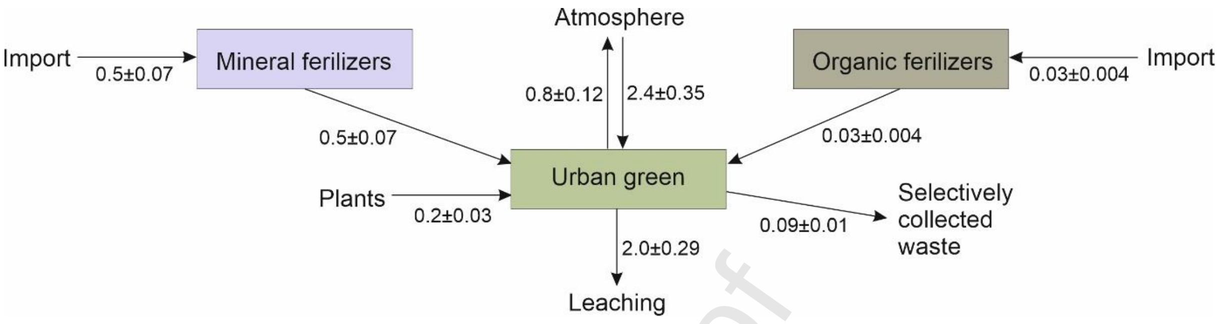


Fig. 5. N mass flows (t N·yr-1) related to agricultural activity on agricultural land in 2015; a. (top) in the core of the city of Zielona Góra (ZG-C), b. (bottom) in the New District of the city of Zielona Góra (ZG-ND)

Nitrogen flows in the city are also related to the functioning of constructed green areas. These areas account for 2.8% of the total area of the ZG-C and 2.6% of the ZG-ND. Nitrogen flows, in addition to general elements for the entire city, are related to both fertilization of ornamental crops, as well as the application of organic garden substrates and the introduction of perennial plants (trees, shrubs, perennials) and in short cultivation cycles (flower beds). The flower plants on beds have been changed in Zielona Góra three times a year – on spring, summer and the autumn.

The latter changes in Zielona Góra three times a year - spring, summer and autumn discounts.

a.



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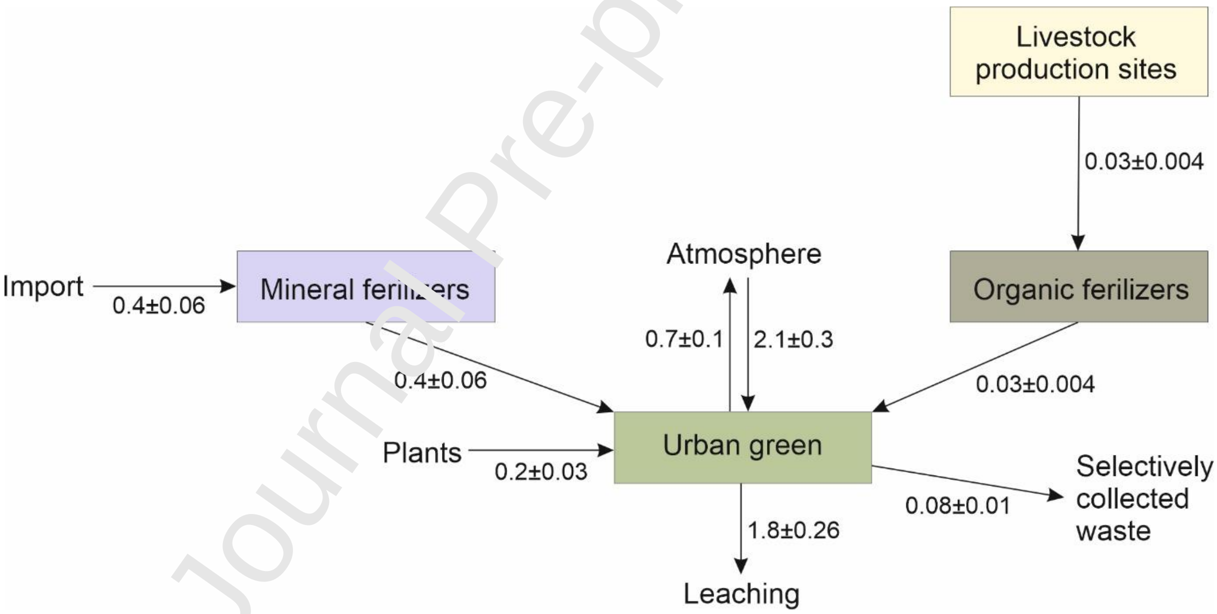


Fig. 6. N mass flows (t N·yr^{-1}) related to the functioning of constructed green areas in 2015; a. (top) in the core of the city of Zielona Góra (ZG-C); b. (bottom) in the New District of Zielona Góra (ZG-ND)

The urban greenery, called (with a great simplification) communal greenery is a typical urban form of a land use. City parks are complex forms, covering areas ranging from communal forests to small areas of the so-called pocket parks. A common feature of the parks is the thinning of the tree stand in relation to forest production areas. The tree stands are subject to maintenance, including mainly cleaning the surface of falling leaves and branches, as well as cutting tree crowns and forming shrubs.

With regard to the circulation of N, attention is paid in cities to both atmospheric deposition, from numerous sources of air pollution (NO_x or NH_3), and direct application resulting from the use of fertilizers, horticultural substrates, sewage sludge and composts. The N content in the soils of urban green areas is generally calculated at 0.02-2.0%, but most often it does not reach 1.0% (Huot et al., 2017; Cambou et al., 2021). Atmospheric deposition can enrich soils by 20-30 kg $N \cdot ha^{-1}$ per year, as demonstrated in the area of Berlin (Wessolek et al., 2011).

Inhabitants of Zielona Góra keep a large number of pets, mainly dogs and cats. There are an average of 4.42 dogs and 3.37 cats per 1 ha of ZG-C, while for ZG-ND these statistics are: 0.19 dogs and 0.15 cats. In addition, there are stray animals, with 0.02 dogs and 0.45 cats per 1 ha in ZG-C, and 0.23 cats in ZG-ND. According to data from the Annual Report of the Chief Veterinarian of the Republic of Poland, the number of dogs and cats per family is similar to other Polish cities. However, their distribution is different due to the peculiarities of the ZG area – the division of the city into the typically urban part of ZG-C and the rural part of ZG-ND. The presence of pets is associated with the generation of waste in the amount of 17.04 $kgN \cdot ha^{-1}$ per year in the ZG-C and 1.08 $kgN \cdot ha^{-1}$ per year in the ZG-ND. The problem is to indicate the amount of waste from the stream described that goes to the landfill, due to its presence in mixed waste. In Poland, it cannot be included in selectively collected bio-waste. In addition, dogs are systematically taken out for walks, during which they fulfill their physiological needs, with an unspecified degree of waste as owners clean up after their pets. However, it should be expected that it is not greater than 10%. Cats, in turn, are kept in the city as both indoor and outdoor pets. 100% of the waste of the indoor cats goes to the waste collection point, while – for outdoor cats only about 20-30% h on an annual average with a clear difference in individual seasons. In ZG-C there is also one place where horses are kept for recreation - 17 heads, and in ZG-ND there are three such places (one of them with an additional sporting role) with a total number of 97 heads. Due to their small number, the production of nitrogen with waste is only 0.13 kg per ha in ZG-C and 0.20 kg per ha in ZG-ND. It is almost entirely a controlled stream, mainly associated with animal dwellings. A small part remains in forest areas during recreational trips. A specific form of enriching urban soils with nitrogen are dog and cat excreta, mainly in landscaped green areas. The mass from 34 to 269 kg of N enters dog parks every day with the urine of these animals.. This nitrogen can further form a soil deposit, infiltrate deep into the soil profile as ammonium NH_3 and released to the atmosphere as N_2O (Petrovic, 1990), and at soil pH > 8.0 or in conditions of high soil compaction, waterlogging, and fertilization with sewage sludge – in the form of gaseous ammonia or molecular nitrogen (Toor et al., 2020). Also in this case, a large part of the nitrogen is present in the soils in the form of nitrates, which results in a three-fold increase in the content of this form compared to zones free of pets (Paradeis et al., 2013).

A separate category, extremely important in the conditions of Zielona Góra, is the forest area, which occupies 45.1% of the total ZG-C and 57.5% of the ZG-ND. They are 92% pine forests: 55% fresh, 9% dry, 3% moist, 20.9% mixed fresh, 4.2% mixed moist, with 87% share of Scots pine in the species structure of stands. They are maintained in accordance with existing forest management plans. Zielona Góra forests are characterized by a nitrogen stock in the litter at the level of 774 $kgN \cdot ha^{-1}$ with an annual growth in a well-developed forest sand of 45 $kgN \cdot ha^{-1}$. Additionally, 540 $kgN\ ha^{-1}$ is deposited in mineral humic horizons of sandy forest soils. The stand contains a nitrogen deposit of 1,396 $kgN \cdot ha^{-1}$ in the ZG-C area and 1,886 $kgN \cdot ha^{-1}$ in the ZG-ND area.

5. Discussion: Management of nitrogen flows in urban space

Two main flows of urban reactive nitrogen can be distinguished in urban systems: the “urban agro-food chain” – covering conventional and urban agriculture, households, commerce, waste water and waste, and the “urban combustion chain” – covering industry, combustion and air (Winiwarter et al., 2020). The analysis of reactive nitrogen flows in ZG-C and ZG-ND indicates that on an urban scale, the interconnections between these chains are marginal. In addition, the marginalization of industry in the city for the development of service sectors can be clearly seen, hence the "urban agri-food chain" becomes more dominant in the context of flow management Nr. A similar trend was noted by in other cities as well as described by Kaltenegger et al. (2023).

Taking this into account, it can be concluded that the sustainable management of reactive nitrogen flows in ZG-C and ZG-ND should cover the following areas:

- waste management (minimizing the amount of generated waste, reuse, recycling),
- water management (reduction of water consumption, reuse, creation of small retention systems, protection against pollution),
- energy - reducing the consumption of non-renewable energy (increasing the amount of energy consumed from renewable sources),
- protection and reclamation/restoration of urban ecosystems as valuable environmental resources.

In the years 2009-2015, there was a major change in the urban space of Zielona Góra resulting from the merger of urban and rural communes with different land use characteristics. Built-up areas (including roads) in ZG-C in 2015 occupied 27.0% of the total area of the city. This index for the ZG-ND area was only 6.7% in relation to the total area of the former rural municipality. In both cases, the area of housing and road development was similar, respectively: 1585 and 1566 hectares. In both cases, however, these were similar areas under cubature and road development, 1585 and 1566 ha, respectively. In both areas the share of agricultural land was similar - 9.3% and 8.5%, respectively, but due to the different sizes of the described areas, it meant 495 vs. 6775 ha. The areas of greenery shaped in both parts of the city occupied a similar area, in ZG-C 153 ha, and in ZG-ND 135 ha. In relation to the total area, greenery accounted for 2.6 and 0.6%, respectively. In ZG-C, in the period 2009-2015, a loss of 48 ha of agricultural land and 35 ha of forest land was recorded in favor of urban development. A large part of the new development was also implemented on previously unoccupied construction areas - approximately 40 ha, post-industrial areas - approximately 30 ha and at the expense of landscaped green areas - approximately 9 ha. Differences in the form of land use translate into N flows related to mineral and organic fertilization as well as local generation and management of waste.

The entire urban structure - ZG-C and ZG-ND is covered by the municipal management system, including the waste collection and management system. Nevertheless, residents are left with the option of self-management of some of them, e.g., compostable waste. This creates differences between the described units, which are visible in the morphological composition of the waste delivered to the ZZO and to the municipal waste landfill. The compost produced by the inhabitants in farms and home composters goes to cultivated areas - mainly within the garden. The compost produced in ZZO goes to the landfill in its entirety as a transfer and closing layer. The difference in waste streams is described by 32.2 kgN·ha^{-1}going to the landfill from agricultural land and greenery in the ZG-C area and only 2.05 kgN·ha^{-1} kg from ZG-ND. In accordance with the idea of closing the cycles of elements and waste-free management, the practice regarding the circulation of waste containing organic matter should be changed. Compost as a valuable fertilizing material should be returned to urban ecosystems, mainly by fertilizing the soils of landscaped green areas characterized by a shortage of assimilable components. This would also reduce the shortage resulting from insufficient fertilization, implemented in principle only on newly established plots and some of representative importance. An important step in this direction is the increase in the recycling of bio-waste, sewage sludge and sewage.

The Waste Framework Directive, as amended in 2018, introduced changes that, among others, oblige EU Member States to separate and recycle at source, or to collect biowaste separately, from 2023. This is a great opportunity to improve the recycling rate of nutrients (nitrogen) contained in waste. Also, the new provisions of the EU Water Framework Directive oblige EU Member States to change their approach to the processes carried out at wastewater treatment plants. The wastewater treatment plant should be a facility for the production of renewable resources.

A new scenario of nitrogen recovery that is expected for the near future is the recycling of biogenic compounds in treated wastewater and their use as fertilizer. This approach reduces the consumption of energy used for the production of mineral nitrogen fertilizer and minimizes eutrophication and greenhouse gas emissions (Saud et al., 2023). Legal requirements for the recovery of components contained in treated wastewater focus primarily on using them as water, which, after meeting the appropriate requirements regarding physical, chemical and biological properties, can be used for irrigation in agriculture and for other purposes (e.g., in industry) (Radini et al., 2023). The use of treated sewage for irrigation (fertigation) may slightly reduce the demand for mineral fertilizers. Most of the Nr found in wastewater is removed in the denitrification process and released into the air as N_2. It leads to major losses of nitrogen that could be used in agriculture (Ofori et al., 2021).

The flow of nitrogen in built-up areas of urban space is strongly changed in relation to that observed in open spaces, developed naturally. The presence of debris in the soil matrix of urban areas substantially changes the conditions of nitrogen circulation in the environment, increasing the outflow of this element from the soil. The compaction of the soil material greatly reduces the infiltration of components into the soil profile, however, it causes the effect of intensive surface runoff (to the sewage system) during periods of increased precipitation, over 10 mm hr^{-1} (Yang and Zhang, 2011).

Soil moisture and the ability to hold water in the soil (water retention) can be regulated by applying fertilization or soil fertilization. An urban lawn on sandy loam showed an increase in water content of 6% with 1.52 cm of compost and 9% with 6.04 cm of compost (Curtis and Claassen, 2009). Soil moisture and the ability to hold water in the soil (water retention) can be regulated by applying fertilization or soil fertilization. An urban lawn on sandy loam showed an increase in water content of 6% with 1.52 cm of compost and 9% with 6.04 cm of compost (Curtis and Claassen, 2009). Introducing water retention in urban areas can reduce nitrogen runoff from the urban area into receiving bodies and improve nitrogen cycling in the city.

A largely unresolved nitrogen-related problem in urban space is the stream of nitrogen associated with keeping dogs and cats in households. With substantial numbers of these animals both in the ZG-C and ZG-ND, the stream of nitrogen reaching the soils of landscaped green areas and forests is unrecognized. At the same time, it is a dispersed stream due to the lack of regulations regarding the separation of places related to the presence of people with and without animals, which is already a standard in many cities (King and Long, 2004; Urbanik and Morgan, 2013; Kulesza and Lubiarz, 2016; City of Vancouver Park Board, 2017; Ferreira et al., 2017; SP&R, 2017; Fischer and Kowarik, 2020; Allen et al., 2021; Berlin T&K, 2023; top10 Vienna, 2023). With the total number of dogs and cats for the entire area of the Zielona Góra agglomeration amounting to approximately 30,000 of each kind, this is a big problem for the urban environment.

Based on the analyses carried out, it can be concluded that intensively populated places (with large flows of Nr import for different purposes of consumption) are also the largest emitters of Nr pollutants. In addition to Nr, these places also emit the largest amount of greenhouse gases from the combustion of fossil fuels. Based on the Nr flow model presented for Zielona Góra, it is possible to prepare a policy mitigating the impact of pollutant emissions on climate change caused by a traditionally developing economy.

The proposed changes in urban policy should aim at achieving a circular economy, taking into account distributed energy, which draws energy and heat from biogas plants, minimizing the combustion of hydrocarbons. Reducing Nr flows can partly be achieved by increasing recycling. In ZG-C Nr is not recyclable. Selectively collected waste and sewage sludge are recycled off-site. The situation is different in the suburban area, where manure from agricultural production is managed entirely on agricultural land (recycling rate is 21%).

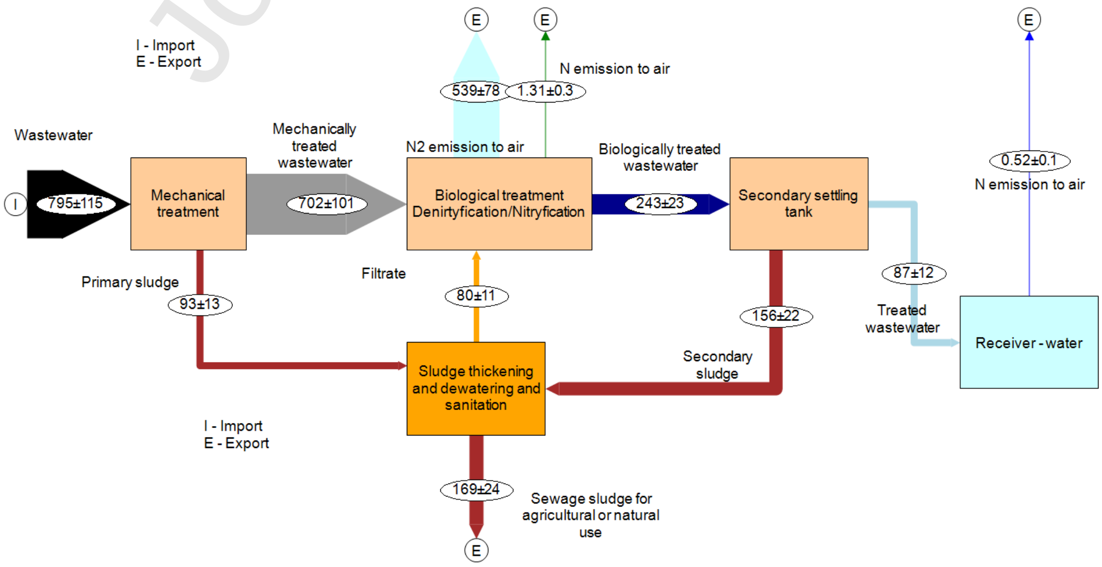
5.2. Developing scenarios for Nr flows in waste and sewage management

Food consumption is an important consideration when balancing Nr in an urban environment. Waste nitrogen from food is metabolized in the household pool, from which it exits as waste and wastewater to the respective treatment plant for further processing. The largest share of nitrogen in waste generated in urban environments is found in sewage sludge and food waste (Buckwell and Nadeu, 2016). The recovery and recirculation of nitrogen contained in waste is an important Nr management strategy in the city. Hence, it seems useful to select waste and wastewater sectors to view possible future situations of Nr flows. The type of wastewater treatment and waste treatment technology used, the way it is collected and transported, and the amount of nitrogen recovery and reuse have a major impact on nitrogen emissions. The main sources of N_2O emissions are wastewater treatment, sewage sludge incineration, municipal solid waste incineration, biomass combustion for energy production, waste fuel combustion with high nitrogen content. From the waste sector, there are mainly NH_3 emissions generated in the composting and storage process and, to a small extent, N_2O emissions generated at each stage of waste management. In the composting process, approximately 98% of N emissions are NH_3 and 2% are N_2O (Barton, et al., 2002). Waste incineration generates mainly NOx emissions. Both NO_x and NH_3 emissions from waste indirectly cause N_2O emissions (Beck-Friis et al., 2001).

WASTEWATER:

The nitrogen balance for the base year 2015 is shown in the fig. 7a and for the 2030 in the fig. 7b. The amount of Nr that leaves the WWTP in 2015 as sewage sludge was 170 t N·year^{-1}. From the wastewater treatment there are emissions of 539 t N·year^{-1} to air and 87 t N·year^{-1} to receiver water. The use of anaerobic stabilization (methane fermentation) reduced the amount of nitrogen available in the sewage sludge for use as fertilizer. In the forecast the amount of Nr available as sewage sludge is 122 t N·year^{-1} (Fig. 7b). The emissions to air will be 612 t N·year^{-1} from biological wastewater treatment and 19 t N·year^{-1} with biogas.

a.



b.

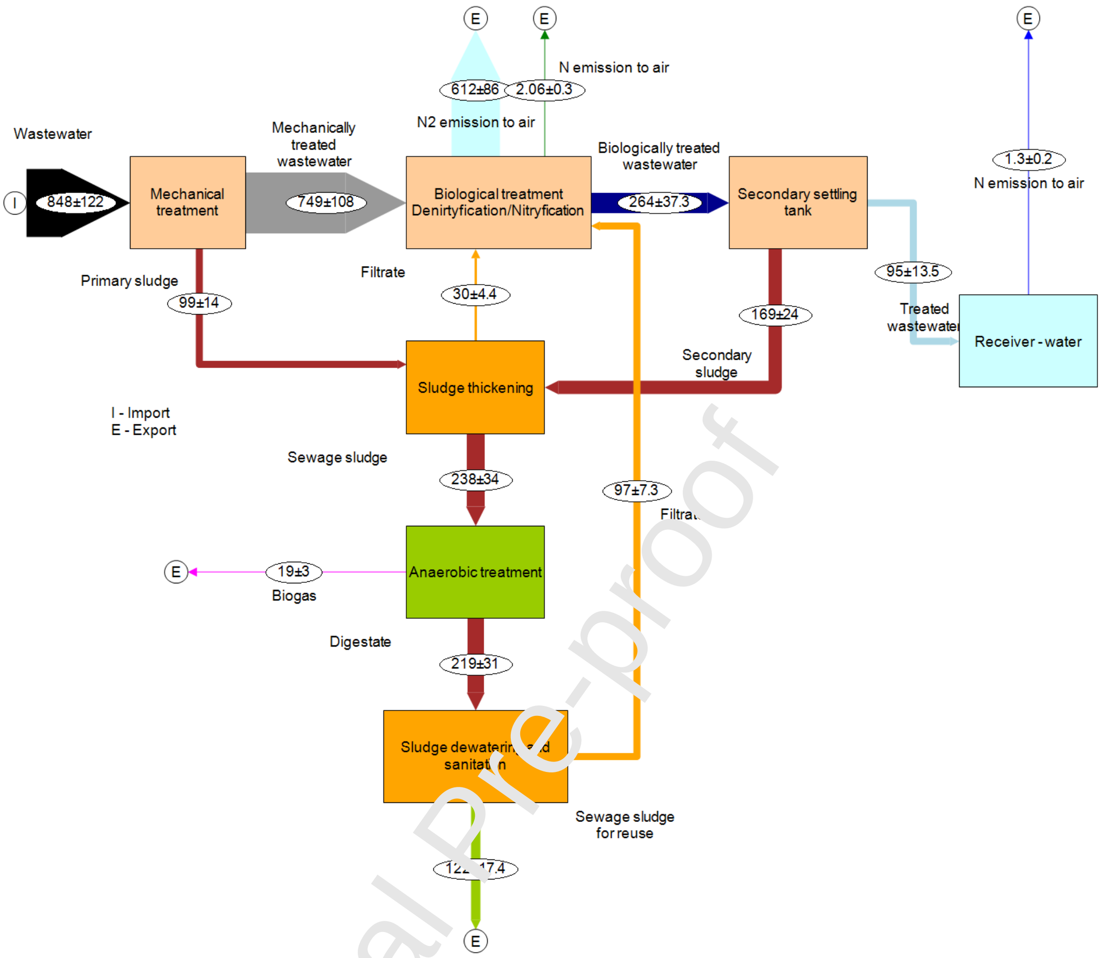


Fig. 7. Nitrogen cycle (t N·year^{-1}) in a wastewater treatment plant a. (top) in 2015, b. (bottom) in 2030

A new opportunity to improve the nitrogen recycling in the WWTP system is recovery by reusing water (treated sewage). Such action additionally causes that nutrients are not returned to the beginning of the treatment plant, contributing to the reduction of energy consumption in the entire system, and their recovery reduces the process of eutrophication of receiving waters and uncontrolled emission of greenhouse gases. According to the EU regulation **(**2020/741) on minimum requirements for water reuse for irrigation in agriculture, re-using wastewater can contribute not only to the reduction of drinking water consumption, but also to the development of a closed-loop economy through the recovery of nutrients and their use in crops using fertigation techniques. At the same time, the possibility of using ecological fertilizers is created. Wastewater reuse has the potential to reduce the need for additional mineral fertilizer applications and can be a way to reintegrate nutrients such as nitrogen, phosphorus and potassium into natural biogeochemical cycles. However, this method of water reuse is only used to a limited extent in the EU. This appears to be partly due to the substantial cost of wastewater reuse systems and the lack of common EU environmental and health standards for water reuse. In particular for agricultural products, potential health and environmental risks and potential obstacles in the free movement of such products which have been irrigated with reclaimed water (Radini et al., 2023; Ofori et al., 2021).

Despite this, it should be assumed that water reuse is inevitable and will soon be mandatory. For the Zielona Góra agglomeration, this gives an opportunity to manage water to be used for irrigation and fertilization of at least urban green areas (ZGND 135 ha). Assuming that Nr from treated sewage, (95 t N·year^{-1}), could be used as fertilizer, half would be enough to fertilize all urban greens areas in ZG-ND. Doses for more frequently mowed lawns, e.g. ornamental, nitrogen fertilization should be applied up to 200-250 kg N·ha^{-1}·year^{-1}, while for intensively used lawns, e.g. sports lawns, it is recommended to use 300-400 kg N·ha^{-1}·year^{-1}. Lawns mowed 3-4 times during the growing season should receive annually 100-150 N·ha^{-1}·year^{-1} (Wang et al., 2014; Bilgili et al., 2005). Sousa et al., (2011) stated that irrigation with treated wastewater showed a positive effect on lawn installation through higher growth of grass (1,667 cm) and higher dry matter yield (18,147 gm^{-2}) as treated wastewater contains nutrients necessary for plant growth such as N, P, and K, and micronutrients such as Fe, Mn, Zn, and Cu, and as well as organic matter. However, poor management of irrigation could contribute to environmental problems. High components concentration in treated wastewater can be too high for grass, therefore leading to nutrient leaching and soil salinity (Hashem et al., 2021). Of course, the main difficulty is the transport of treated wastewater and the costs associated with distribution and pumping. But the reuse of water only for irrigation and fertilization of flowerbeds in the city by individual car transport can bring additional ecological and economic benefits.

A method that is technologically mature enough to be used commercially in WWTP for recovery of Nr is the separation of struvite using fluidized bed reactors, which renders mineral fertilizer as a directly usable product (Tansel et al., 2018). Struvite ($MgNH_4PO_4{\cdot}6H_2O$) can form spontaneously in wastewater treatment plants, which creates operational problems. High concentrations of ammonia in filtrates and effluents from wastewater treatment plants promote the precipitation of struvite. Typical nutrient content of struvites is: 4.7-5.6% N (w/w), 28-29% P_2O_5 (w/w), <1.0% K_2O (w/w) (Siciliano et al., 2020). Another method is membrane filtration combined with an ion exchange process to recover ammonia from wastewater and digestate. An NH_3 - N recovery of 37.5% was reported (Hui et al., 2017).

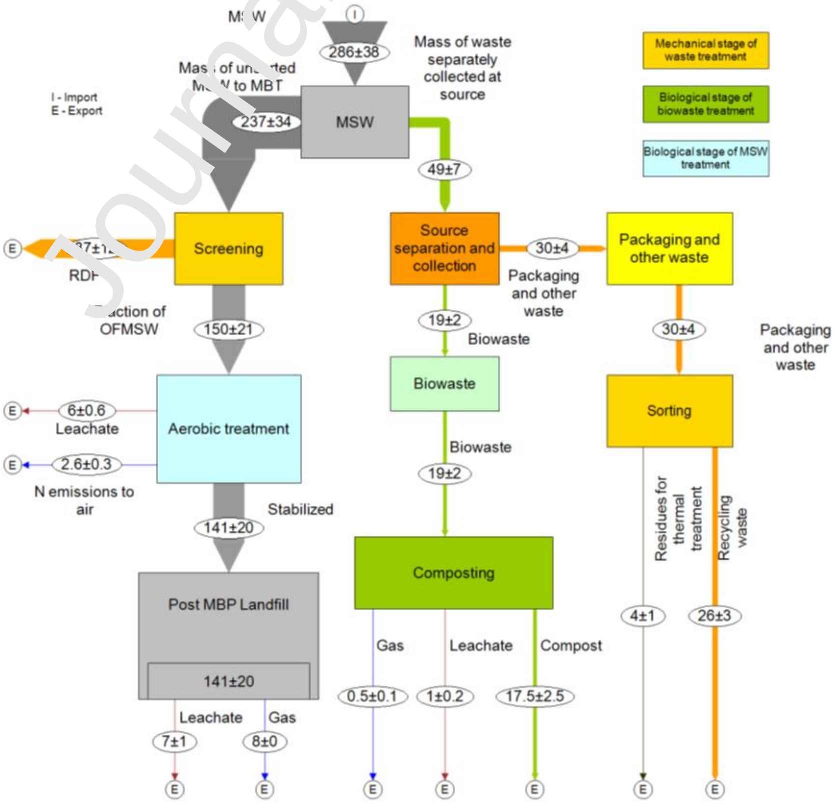
But the most important and basic recovery method of Nr is sewage sludge directly used for fertilization purposes. Currently, when the raw material crisis is deepening, rising prices and the problem with the availability of natural gas have made the production of nitrogen fertilizers very expensive, the availability of fertilizer nitrogen from biological wastewater treatment plants is of particular importance (Chojnacka et al., 2023). However, the introduction of these components into the soil along with the sludge should be in line with the generally applicable fertilization principles, while respecting the principles of environmental protection, including, among others, soil and water protection (Sichler et al., 2022). Determining the dose and carrying out quality tests is extremely important to meet and maintain the purpose of using municipal sewage sludge. Such action leads to the complete closing of the cycles of substances and substrates obtained in the process of wastewater treatment in WWTP. This is the best way to use and improve the nitrogen balance of the ZG.

WASTE: The nitrogen content in waste and sewage and its mass depends on diet, standard of living, degree of economic activity, season, dynamics of economic development, cultural conditions, technical and sanitary equipment, type of industry and its efficiency. Residues from the sorting plant, bulky waste, oversize fraction and aerobic stabilized waste are sent to the regional municipal waste landfill. The mass values of these fractions are shown in Table S6 S8 presented in the supplementary materials.

The mechanical-biological waste treatment installation consists of a mechanical stage equipped with a rotary screen with a mesh diameter of 80 mm and a baling press, and a biological stage to which the under-sieve fraction (fraction < 80 mm) from the mechanical part is directed. The oversize fraction (fraction > 80 mm) is sent to the sorting plant and then (after initial treatment consisting of sorting out bulky waste, scrap and mineral waste) to plants producing alternative fuel or to a landfill.

The installation for biological waste treatment in Zielona Gora city consists of six lines of technological chambers in which the processes of aerobic stabilization of residual waste and composting of bio-waste are carried out. The aerobically stabilized waste from the installation for biological processing of the under sieve fraction and compost is directed to the mechanical treatment line, where it is separated into fractions on a rotary sieve with a 40 mm and 20 mm where ferrous metals and fine glass fractions are recovered. Waste fraction after aerobic treatment <20 mm and the composting product are sent to the landfill for initial reclamation of the landfill. Waste fraction after aerobic treatment >20 mm and composting residues are sent to landfill. Mass streams of nitrogen in waste sent to MBT calculated for the base year 2015 are presented in Fig. 8a and for 2030 in Fig. 8b.

a.



b.

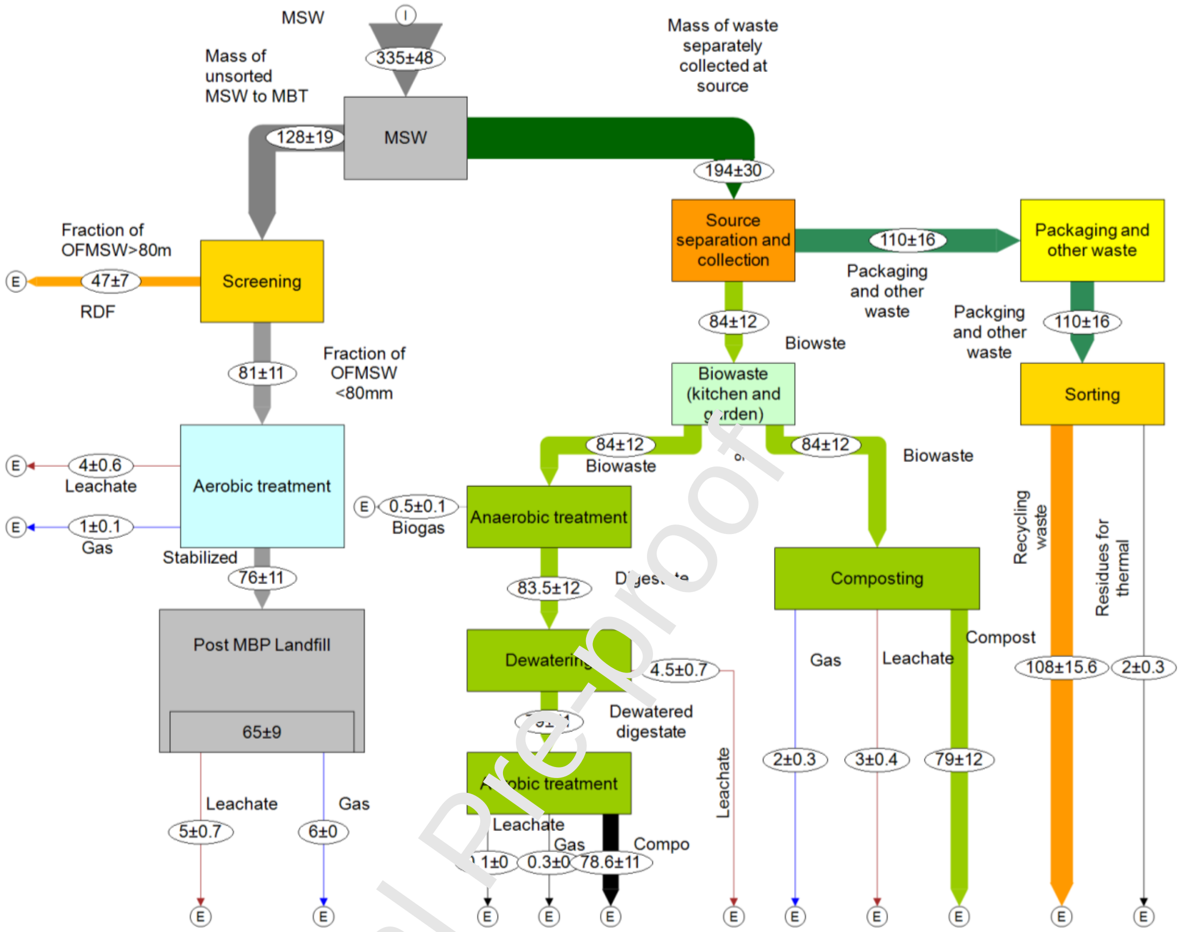


Fig. 8. Nitrogen cycle (t N·year^{-1}) in a MBT a. (top) in 2015 and b. (bottom) in 2030

In the Waste Management Plant, Nr emissions are observed practically at every stage of processing. They are related to nitrogen present in the organic fraction of municipal waste. The highest nitrogen content in municipal waste (MSW) is observed in the fraction of kitchen and garden waste (biowaste). According to the European Topic Center on Sustainable Consumption and Production (ETC/SCP), bio-waste accounted for 37% of the mass of municipal waste in Europe (EU27 excluding Cyprus) in 2008-2010 (Biowaste selective collection, 2016). In Poland, the share of biodegradable waste in municipal waste in 2021 was about 31% (Jędrczak, 2021).

Other fractions of municipal waste rich in nitrogen include clothing and textiles, paper and cardboard, large-size packaging and wood. Nitrogen contents of individual waste fractions are presented in supplementary materials (Table S9). Mass flows of nitrogen in ZZO installations are closely correlated with the way of managing MSW in the city. In the perspective of 2030, the method of municipal waste management in the city will have to undergo a material change.

According to the revised Waste Framework Directive of 2018, EU member states are obliged to separate and recycle at source or to separately collect bio-waste, from 2023. New targets for the recycling of municipal waste have also been set. In 2025, 55% of the mass of municipal waste generated should be recycled, in 2030 - 60%, and in 2035 - 65% (Directive 2018/851). New target values for the recycling of packaging waste have also been set. The adopted very ambitious targets for preparing for re-use and recycling of municipal waste will not be achieved without a high level of bio-waste recycling. Selectively collected biowaste, due to its high moisture content and susceptibility to biodegradation, is suitable, above all, for composting and fermentation.

Analyzing the mass flows of nitrogen presented in the diagrams, it can be concluded that the intensive development of selective waste collection will result in a decrease in the mass of residual waste delivered to the MBT installation. The required installation capacity for Zielona Góra in 2030 will decrease from approximately 35,000 to 19,000 $t \cdot yr^{-1}$. The released capacity of the MBT installation should be used, after modernization, for sorting selectively collected raw materials (mechanical part) and for composting or fermentation of bio-waste (biological part), which was recommended in earlier works (Boer, 2018; Połomka, Jędrczak, 2019; Favoino, 2020; Benart et al., 2022). This will lead to reduction in emissions of pollutants to the environment from these installations, including nitrogen emissions, thanks to, among other things, an increase in material recycling and the production of fertilizers that will be returned to the soil environment.

The analysis of nitrogen mass flows presented in Fig. 8 also shows that, taking into account the amount of nitrogen emissions, the objectives of the Waste Directive and the need to increase the share of energy consumption from renewable sources, the most beneficial waste management system for Zielona Góra will be a system in which separately collected bio-waste will be processed under anaerobic conditions. This system allows for the recovery of energy from biogas and the reduction of nitrogen emissions into the air. It also ensures low nitrogen losses during the processing of biowaste, compared to the composting process, and thus higher nitrogen recovery. The change in the municipal waste management system leads to the production of a valuable fertilizer that should be used in urban and suburban areas of Zielona Góra.

The path to a circular economy requires the development of new technologies focused on the processing of bio-waste. Technologies to produce organic-mineral fertilizers from bio-waste are already known, allowing for high-efficiency return of nitrogen to the soil or recovery of nitrogen from leachate, permeate or digestate. However, these methods are not yet commercially applicable on a large scale.

6. Conclusions

Zielona Gora is a city with a specific functional and spatial structure resulting from the combination of an urban municipality and a rural municipality into one system. Thus, it is characterized by a large total area (in 2022 the sixth city in Poland) and a relatively small number of inhabitants (24th place in the country in terms of population) and the share of built-up areas (only 13%). As a result, many nitrogen fluxes are characteristic for agricultural activities, typical for rural and partly suburban areas. Large flows (especially in the ZG-ND) are associated with soil fertilization, crop harvesting and animal husbandry, which is unusual for European cities. However, changes in this aspect are already evident, for example, in the form of reduced soil fertilization, abandonment of some fields, a change in theirs character to recreational and leisure use, and progressive land development.At the same time, the stream of nitrogen related to consumption and housing (consumption of food, fuels, waste and sewage production) is strongly noticeable. Already, ZG-ND is effectively an "urban sleeping area". Facilities requiring large areas, mainly related to logistics, are also being built there. In 10-20 years, this will equalize the N rates for both parts of the city, while agriculture will remain a relic of the old days, as it already is in ZG-C.

In addition, a strong trend towards rapid extensive development is observed, especially in the area of New District located in the area of the former rural commune. Due to this condition, there are visible differences in the circulation of nitrogen in the core of the city (ZG-C) and its peri-urban (ZG-ND). Most of them concern the differences in the share of agricultural land in both these urban parts, cultivation activities, fertilization procedures, and management of compostable waste, and differences in population density. However, the trend of land use in Zielona Gora, based on urban development built among forests, with the systematic elimination of agricultural land, is evident.

The analysis of urban nitrogen budgets in the ZG-C and ZG-ND allowed to show the differences in the flow of N fluxes in urban and peri-urban environments. Moreover, it showed that:

- in Zielona Góra, the agri-food chain is much more important in terms of N release than the energy/industrial chain,
- N recycling occurs only to a very limited extent – a problem in the transition to a circular economy,
- scenarios for improving the N cycle in the city focus on the recycling of nitrogen contained in biowaste and sewage sludge (fertilization of agricultural land and urban greenery) and the reuse of wastewater as a source of N and for irrigation of fields.

The release of Nr into the environment is closely related to the combustion of fossil fuels, the production and consumption of food and the management of waste, especially organic waste and wastewater. Factors influencing the scale of this phenomenon are related to, among others: population density, structure of buildings with the road network, industrialization, consumption of material goods food and energy, as well as the intensity of urban and suburban expansion. Reactive nitrogen is mainly imported in food and fuels, and in suburban areas, additionally with fertilizers and livestock. It is then accumulated in soils and/or emitted to air, water and other ecosystems with its impact extending beyond the city borders (Svirejeva-Hopkins et al., 2011).

Reducing Nr flows can partly be achieved by increasing Nr recycling. However, when investigating the situation in ZG-C and ZG-ND, we found that Nr is not recyclable because selectively collected waste and sewage sludge are recycled off-site. The situation is different in the suburban area, where manure from agricultural production is managed entirely on agricultural land (recycling rate is 21%).

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The data that support the findings of this study are openly available in the supplementary material. The STAN model for urban nitrogen budgets is openly available on the STAN platform as "Urban Nitrogen Budgets" (https://www.stan2web.net/downloads).

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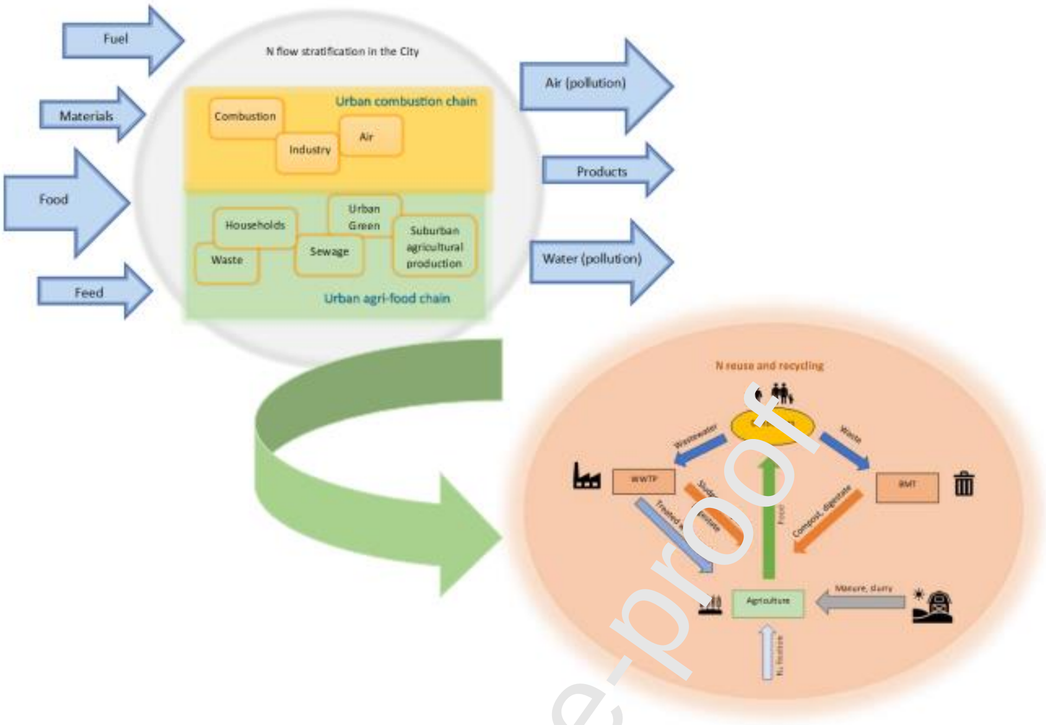
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



Graphical abstract

Highlights

- Nr cycle is more affected by human activities than the global carbon cycle.
- Exceeding Nr limits has serious consequences for health and environment.
- The largest N flows occur along the urban agri-food chain.
- Improving Nr circulation is possible by Nr recycling/recovery from waste and sewage.