Chapter 12

Nitrogen flows and fate in urban landscapes

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Executive summary

Nature of the problem

- Although cities take only 1.5%–2% of the Earth's land surface, due to their dense population, settlement structure, transportation networks, energy use and altered surface characteristics, they dramatically change the regional and global nitrogen cycle. Cities import and concentrate N_r in the form of food and fuel, and then disperse it as air and water pollution to other ecosystems covering much larger areas.

Approaches

- A mass-balance approach was used in order to quantify the fluxes of reactive nitrogen (N_r) in and out of cities.
- Cities can be characterised either as a source of N_r (i.e. emitting large amounts as liquid or solid household waste, automobile exhaust, air pollution from power plants) or a sink of N_r (through importing more food, fossil fuels, etc., and having fewer emissions to the air and water).
- Paris metropolitan area is used as a case study, which represents an evolving European capital with much available data.

Key findings/state of knowledge

- The Paris Metropolitan Area changed from being a sink in the eighteenth and nineteenth centuries to a source of N_r today. Major changes in the city functioning occurred before 1950, but especially recent decades have been characterised by an unprecedented amplification of those changes.
- The major part of N_r output is attributed to the combustion of fossil fuels for transport and energy, which converts both atmospheric N_2 and fossil N_r to reactive NO_x. The second largest N_r contribution comes from incineration of solid waste, and third highest emissions come from sewage water treatment plants.
- Urban wastewater discharge into rivers largely contributes to N contamination of the aquatic environment, although sophisticated and expensive tertiary treatment techniques are now available to drastically reduce N_r emissions.
- Denitrification in urban landscapes is controlled by the presence of water bodies and green areas. These areas have lower biomass and decomposition rates than natural ecosystems.

Major uncertainties/challenges

- A better understanding is needed regarding the following uncertainties: (a) the mechanisms of dry-deposition in urban systems with patchy vegetation; (b) the complex patterns of air flow in densely built-up areas; (c) the fate of N_r in urban soils with altered water regimes and impermeable surfaces.

Recommendations

- To achieve sustainability of urban systems in relation to the N cycle, road transport of goods and passengers has to be reduced, household waste generation minimised, and wastewater treatment improved.
- More attention should be given to future sewage processing systems that process N_r (and other nutrients) for reuse as a fertiliser rather than losing the N_r resource by denitrifying it back to N_2.
- Such measures could eventually turn urban areas from sources of N_r to N-neutral or even N-sink areas. Regional adaptation measures should be specifically tailored to the individual urban ecosystems of Europe.

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12.1 Introduction

12.1.1 Problem setting and approach

In this chapter we ask and try to answer the following questions: what are the specific features of urban landscapes in Europe and how does the local urban N cycle differ from that for natural ecosystems? What are the important issues concerning N management in cities in Europe as a region? As a case study we chose Paris for a more in-depth quantification of terrestrial and atmospheric fluxes, input and output to the system-city.

But first of all, why is a chapter dedicated to nitrogen fluxes in urban systems required for the European Nitrogen Assessment (ENA)? Although cities take only 1.5%–2% of the Earth's land surface, due to their dense population, settlement structure, transportation networks, energy use and altered surface characteristics, they change the N cycle substantially. Firstly, they fix substantial amounts of atmospheric N_2 to N_r as NO_x through the high temperature combustion of fossil fuels. Secondly, they drive the industrial fixation of N_r to fertilisers, importing the N_r produced in food for burgeoning urban populations, subsequently dispersing it in air and water pollution to other ecosystems over much larger areas than the cities themselves. In other words, they act as concentrators, transformers and dispersers of N, representing new entities of the Earth System.

We use an ecosystem approach in this chapter. Any ecosystem is an open system, whose functioning is supported by in- and out-fluxes of matter and energy. These fluxes constitute the system itself and determine its boundaries (Odum, 1973).

12.1.2 The city as an ecosystem

Any city, and especially an industrial one, represents an incomplete or 'heterotrophic' system, receiving energy, food, materials, water and other substances from outside of its boundaries. The city could be considered as a specific heterotrophic ecosystem that differs very much from a natural heterotrophic ecosystem. In fact, a city has a more intensive metabolism per area unit, requiring a significant inflow of artificial energy. Its consumption per urban area unit may be three to four orders of magnitude higher than for a same-sized rural non-agricultural area. One hectare of the city area may use 1000 times more energy than the same area of the rural territory. During the process of its own metabolism, a city consumes large amounts of various materials: food, water, wood, metals, etc., all that we call 'grey energy'. Products of city's metabolism are large volumes of substances that are more toxic than those produced by natural ecosystems. Most cities have wide green belts (consisting of trees, bushes, lawns, as well as ponds and lakes), so it could be said that some autotrophic component is also present.

Wakernagel and Rees (1997) introduced the concept of the ecological footprint, which provides an account of the total area of productive surfaces required to produce, under prevailing technology, the resources consumed by a country or a city. Feeding modern cities is associated with one-third to half of the global ecological footprint, ranging world-wide from 0.8 to 3.8 global-hectares per inhabitant (WWF, 2002). This simple 'footprint' indicator, however, neither fully describes the complexity of the relationships that a city establishes with its rural hinterland for the supply of food, nor how, over time, these relationships impact upon the development of both the city and the countryside.

Billen *et al.* (2009) introduced the so-called 'food-print' indicator that takes into account the area required for producing agricultural goods, being expressed in terms of the effective surface of the surrounding territory needed to support the food requirements of a city. Billen *et al.* (2009) found that despite a 50-fold increase in the population of Paris since the fifteenth century, the food-print of the city barely increased twofold. In contrast, the further doubling of the population in the twentieth century was paradoxically accompanied by a fivefold decrease in the food-print, because of the intensification of agricultural production. While emphasising the scale of the changes for Paris, this example also illustrates that the 'food-print' is only a partial indicator of the impact of a city. For example, it does not include a comprehensive account of all resources required, such as energy, fertilisers and waste disposal, which might be converted into additive 'global hectare equivalent' units.

From an ecological point of view, a modern city could be defined as a 'parasite' of its rural surroundings. As things are at present, a city does not produce significant quantities of food or other organic substances, it does not purify its air and it does not return water or inorganic substances to the pristine state of their respective biogeochemical cycles. However, theoretically, one could consider a city from a different perspective, for example looking at it as being in a symbiotic relationship with its environment, because a city produces and exports goods and services, money and cultural values, receiving in return goods and services as well.

12.1.3 The urbanisation processes

Urbanisation is considered to be one of the most powerful and characteristic anthropogenic forces on Earth in the twenty-first century. Although, as noted above, cities occupy only 1.5%–2% of the Earth's land surface, they are home to over 50% of the world's population. The number of city dwellers has increased from a mere 14% of world population in 1900 and will further increase to an estimated 60% by 2030 (UNCHS, 2003). The total number of people living in major European cities in the 1400s was only 1.1 million, increasing to 3.5 million in the 1700s, and 3.8 million in the 1800s. However, during the twentieth century, an exponential growth of urban dwellers took place, accompanied by a large increase in the number of large cities (Hohenberg and Hollen, 1985). At present, urbanisation processes in Western Europe have reached the so-called 'stagnation period', giving an example of saturated growth. This is, however, accompanied by the expansion of medium-sized cities (~1–2 million). The dynamics of European urbanisation, the differences between urban patterns in Western and Eastern Europe and the implications for the terrestrial, water and atmospheric parts of the N cycle are discussed in greater detail in the following sections.

The N cycle, one of the main cycles in 'Biosphera Machina', is closely interconnected with the carbon, water and oxygen cycles. Urbanisation-related disturbances in the main driving cycles, caused by urban human activities, lead to global, regional and local environmental problems, such as global warming, photochemical smog, soil acidification, and eutrophication pollution of surface, ground and coastal waters. Even though in some cities urban population might stabilise or even slightly decrease, actual urban areas as such are expected to continue to expand in the twenty-first century, accompanied by growing energy production, increased food demand, and expanding transportation and industrialisation.

The demands of high production to feed the urban population alter land cover, biodiversity, and hydrology, both locally and regionally. Similarly, urban waste discharge affects local to global biogeochemical cycles and climate. Although agricultural production is by far the largest influence which has caused the amount of N_r entering the biospheric cycle to double compared to pre-industrial conditions (Smil, 1999), today more than half the crops produced in rural areas are consumed in urban zones.

Transportation and industry are concentrated in urban centres, making them point sources of N containing greenhouse and other trace gases such as NO_x, N_2O and many organic N_r forms (Pataki *et al.*, 2006). Air and in particular water pollution influence nutrient cycling and primary production in adjacent ecosystems, especially as many major European cities are located along rivers and coastlines. The N_r in solid wastes generated in cities also eventually enters the air and water, affecting biogeochemical cycles, while the extent of influence depends on the vectors by which materials are carried (e.g. rubbish disposed of by landfill or incineration, dispersal of emitted NO_x and NH_3, etc.).

In addition, it is important to study urban areas in the context of the ENA, since two of the five key threats identified in ENA (Sutton *et al.*, 2011, Chapter 5, this volume), namely water quality and air quality, are important aspects of the functioning of urban landscapes. Moreover, pollution generation by cities is a matter of increasing concern, especially when urbanisation outpaces societal capacity to implement pollution-control measures.

Therefore, it is important to assess the current situation and to forecast the dynamics of N biogeochemical functioning of urban landscapes. This chapter discusses the past and current situation and touches upon the future trends of the development of Europe's urban systems that are related to the N cycle.

12.2 Urban geography

12.2.1 Regional physiography

Europe's long historical development has led to well established trade and communication with the rest of the world. Almost nowhere in Europe is far from water, and water routes have historically facilitated contact between peoples and cultures resulting in the circulation of goods and ideas. The earliest European cities were thus built and developed adjacent to water routes. The hundreds of miles of navigable waterways, straits and channels between many islands, peninsulas and the mainland, the accessible Mediterranean, North and Baltic Seas, all provided the routes for the exchange of merchandise. Later, the oceans became the means of long-distance spatial interaction. This historical advantage of moderate distances applies to the mainland as well. No place in Europe is very far from any other place on the continent, although nearby places are often different from each other. Short distances and large differences enable much interaction, which is typical of European geography over the past 1000 years. The climate in Europe is mild and temperate. Europe's biomes (Bazilevich, 1979) are on average high in biomass density; for example, storage of N_r in the deciduous forest that covers large parts of central Europe can be as high as 1100 kg N/ha (for oak-dominated forest including roots). On average, the N_r content in biomass of the deciduous forest biome of Central Europe is 310 kg /ha, while in the mixed forest surrounding Moscow it is estimated at 496 kg N/ha (Bazilevich and Tytlianova, 2007).

European soils are generally fertile. For example, there are many alluvial soils, formed in the river valleys and deltas, used to grow crops for centuries, while the Russian and Ukrainian black-soil ('chernozems') are extremely fertile. The North European Lowland topographic region, extending from Southern Britain to Western Russia, is the most densely populated physical region of Europe and a route of contact between Europeans and their neighbours to the East.

The United Nations (UN) regional classification divides European countries according to their developmental stage as either Highly Industrialised (Western Europe) or Economies in Transition (Eastern Block and former USSR). The dynamics of city development and the process of urbanisation in general, differ somewhat according to region, as discussed in the next sub-section.

12.2.2 Urban demography and projections

The total population of Europe is around 702 million, distributed over a land area of 9.8 million km^2. Following the demographic explosion which started in the middle of the last century, European rates of population growth and of N_r produced by anthropogenic activities broadly matched the global trends, with similar increases during the period 1980 to 1990 (Erisman *et al.*, 2008). However, these growth rates have declined from an all time peak (2.1% per year between 1965 and 1970) to about 1.6% per year, while human influence has increased faster than population growth (Cohen, 1995).

The UN forecasts that virtually all population growth from now until 2030 will be concentrated in the urban areas of the world. In Europe, the percentage of the population living in urban areas is expected to rise from 77% in 2000 to 84% in 2030, with some countries reaching 90%. However, the proportion of people living in very large urban agglomerations is still small: in 2000, 48% of the population in developed countries lived in cities of less than 1 million inhabitants and by 2015 that proportion is expected to rise to 49% (UN, 2008).

Table 12.1 The largest urban areas in Europe, ranked from 200 world largest (base year 2005)

Rank (World)	Country	Urban Area	Population (10^6)	Land area (10^3 km^2)	Density (10^3 person/km^2)
16	Russia	Moscow	13.3	4.5	2.9
22	France	Paris	10.4	3.1	3.4
29	UK	London	8.3	1.6	5.1
38	Germany	Essen-Dusseldorf	7.3	2.6	2.8
52	Spain	Madrid	5.0	0.9	5.2
63	Russia	St Petersburg	4.6	1.9	3.9
68	Italy	Milan	4.2	2.4	4.6
79	Greece	Athens	3.7	0.7	5.4
111	Italy	Naples	3.0	0.8	3.9
124	Italy	Rome	2.8	9	3.2
134	Ukraine	Kiyev	2.5	0.5	4.6
143	Portugal	Lisbon	2.3	0.9	2.5
154	Germany	Frankfurt	2.7	0.7	3.4
155	UK	Birmingham	2.3	0.6	3.8
176	Netherlands	Rotterdam-Hague	2.1	0.8	2.5
181	Hungary	Budapest	2.1	0.9	2.4
183	Germany	Cologne-Bonn	2.0	0.9	2.1
186	Poland	Warsaw	2.0	0.5	3.7

Source: Demographia, 2009.

Not all large urban agglomerations experience fast population growth. In fact, some of the fastest growing cities have small populations and, as population size increases, the growth rate tends to decline. Some European cities are actually shrinking, with Rome having a negative urban population growth rate of –0.04%; for example, Budapest –0.01% and St. Petersburg –0.09% (Demographia, 2009). Some East German cities are also experiencing a reduction of population due to the changing labour markets. However, in general for Europe, even cities with shrinking populations tend to be sprawling in area. In other words, even where there is little or no population pressure, a variety of factors are still driving 'sprawl' (i.e. increase in city area). These changes are rooted in the desire of people to realise new lifestyles in suburban areas, outside the inner city. The factors reflect micro and macro socio-economic trends, e.g. transport quality, land prices, planning policies, cultural traditions and the attractiveness of respective urban areas. Thus, four-fifths of European citizens now live in towns and cities.

As cities start to increase in size, the social infrastructure grows faster than population, i.e. the surface areas of streets, electricity network length, etc., lag behind the city's population growth, while income and certain measures of innovation outpace it (Bettencourt, *et al.*, 2007). According to the same author, individual human needs (housing, employment, household electrical consumption etc.) are scaled linearly for cities of different sizes. This observation provides us with the grounds for using per capita-based calculations later in this chapter.

On a global scale, cities with a population of 0.5 million and smaller are anticipated to grow the most rapidly in the course of the next 50 years. In Europe, already-existing cities of between 0.5 and 2 million inhabitants are projected to expand the most rapidly in the course of the next 40 years, which calls for expansion of the cities considered in the present assessment. The model of Svirejeva-Hopkins and Schellnhuber (2008) estimates that in Western Europe, the total urban area (including cities smaller than 1 million inhabitants) will increase from 1645 * 10^3 km^2 in the year 2010 to 1661 * 10^3 km^2 in 2030 and subsequently decrease again slightly below the 2010 value to 1641 * 10^3 km^2, owing to the saturation in the urban population growth rate. The dynamics are different for Eastern Europe, where urban areas are projected to grow from 133 to 134 * 10^3 km^2 by 2030, then decrease in 2040, and then increase again to 134 * 10^3 km^2 by 2050. There is also a substantial difference in the regional relative urban areas that are currently 40% for Western Europe (of the total land) and only around 2% for Eastern Europe. This indicates the different patterns of urban development – sprawl versus density increase.

City sizes and types

With a population of more than 13 million, Moscow is the largest European urban area today (see Table 12.1). Paris is the second largest, followed by London, Essen-Dusseldorf, Madrid and St. Petersburg. There are, in total, 58 urban areas in Europe with populations of one million and more. An urban area (urbanised area agglomeration or urban centre) is defined as a continuously built up landmass of urban development (Demographia, 2009). It generally defines the 'urban footprint', or the lighted area that can be observed from an airplane at night. This chapter confines urban areas to a single metropolitan area or labour market area. What constitutes a particular metropolitan area is a matter of professional judgment. However, there is a necessity to 'draw a line', especially where adjacent urban areas have 'grown together', but remain fairly distinct labour markets.

Having considered the list of all European cities, we could categorise city types as:

- small cities with a population of under half a million,
- medium-sized cities ranging from 0.5 to 2 million,
- large cities with a population of 3 million people or more.

The so-called combined urban areas ('mega-cities') are not characteristic of Europe; this is a typical American, Chinese, and to some extent Indian phenomenon, while there are no mega-cities in Europe to date. While Moscow and London have populations of 13 and 8 million respectively, they neither have catastrophic urban densities nor occupy vast amount of land, as typical mega-cities do. However, some twin cities are already emerging in Europe; for example Essen-Dusseldorf (Germany), Marseille–Aix-en-Provence (France), and Rotterdam-Hague (Netherlands). In this chapter we focus on the settlements of one million and more, since in terms of N fluxes, they play the role of indirect consumers (N for fertiliser, fixed to 'feed' them) and sources of N_r at the regional scale.

Special consideration, in view of future urban trends, should be given to the type of settlements known as 'new cities' – planned communities, also called 'new towns', since they are still relatively small. Carefully planned from the start and typically constructed in a previously undeveloped area, they contrast with settlements that evolve in an 'old-fashioned' way. There are only a few of them in Europe so far, their populations are small (a few thousand) and some of them are not developing as planned. One successful example is Louvain-la-Neuve, the French-speaking university town in Belgium built in 1972 with originally only 600 permanent residents in it, which has experienced rapid growth, reaching 10 477 inhabitants in 1981. This town is also an example of the 'New Pedestrianism' movement, e.g. where roads are in many cases directed under the city. Another representative new city is Tapiola (population of 16 000), constructed in the 1950s and 1960s by the Finnish apartment foundation and designed as a garden city. An interesting example is the city of Slobomir in Eastern Europe, which aims to become one of the major cities of post-war Bosnia–Herzegovina and Serbia, which is still under construction.

12.2.3 Urban density as an integral indicator

The western part of Europe is characterised by the most uniform demographic processes. France, Europe's second largest country, has the lowest number of large-city dwellers, at only 10.4%. By contrast, Russia has one of the highest figures – 42% of inhabitants reside in large towns and cities. Countries that formed part of the former Soviet Union are similar in that respect. In the Ukraine, 37% of the population live in cities with more than 150 000 residents, in Belarus 40%. The historical development of Germany and Italy led to the formation of a large number of important but smaller cities. In Germany, 26% of the population live in *Großstädten ('large cities*'), while only 21% of Italians reside in cities with populations of more than 150 000 people. Poland is the country where the share of the rural population is the highest: only 24% of people live in large towns and cities. With more than 8 million residents, London alone accounts for almost 12% of the UK population. According to statistics, about 51% of Britons live in towns and cities with more than 150 000 inhabitants. However, this figure could be inaccurate, since some smaller towns have been administratively merged with their surrounding rural districts.

Suburban structure varies throughout Europe depending on the individual city's location, the urban spatial typology, social status and functioning. Today, suburbs are a mosaic of mainly isolated fragments of different housing types, enriched by infrastructure facilities like retail stores and offices subdivided by transport networks. Central Western Europe and especially France and Great Britain have experienced a tough social exclusion of non-privileged classes that have had to settle in compact suburbs consisting of social housing facilities. In Central and Eastern Europe, housing construction was limited to huge, industrialised mass-housing estates. Western-style suburbia never developed, which is one of the core differences between Eastern and Western urban development. Currently, this difference is rapidly disappearing, and luxurious housing estates multiply in the suburban areas of former socialist cities. The urban core is losing its inhabitants, while the suburbs grow as a whole. This is particularly true for Eastern Germany.

Figure 12.1 shows the European part of Tobler's updated world population density map (Tobler, 1995); urban densities are notably redder and large urban areas are detectable. In broad terms, this map of urban density provides an indicator of NO_x emissions intensity, as can be seen by comparison with mapped tropospheric NO_2 concentrations (Beirle *et al.*, 2004; Simpson *et al.*, 2011, Chapter 14, this volume).

In Figure 12.2, one can clearly see that different types of cities form different clouds in the plot. For example, such major cities as Moscow, Paris and London clearly stand out; however their densities are not especially high compared to some unsustainable Eastern European and Russian cities. Samara and Ekaterinburg – although occupying relatively small areas and being only medium-sized – have the highest population densities in Europe with 8.4 and 9 thousand inhabitants per km^2 respectively.

Bucharest, the capital city of Romania, is of medium size (2 million) and is also quite dense. If we look at Table 12.2 showing the time taken to travel to work in a sample of cities, we see that Bucharest is characterised by the highest time of almost 80 minutes. Since the area of city is not too large, this may indicate a high level of vehicle congestion, that the public transport networks are not efficient or that the city has developed without one core financial commercial district,

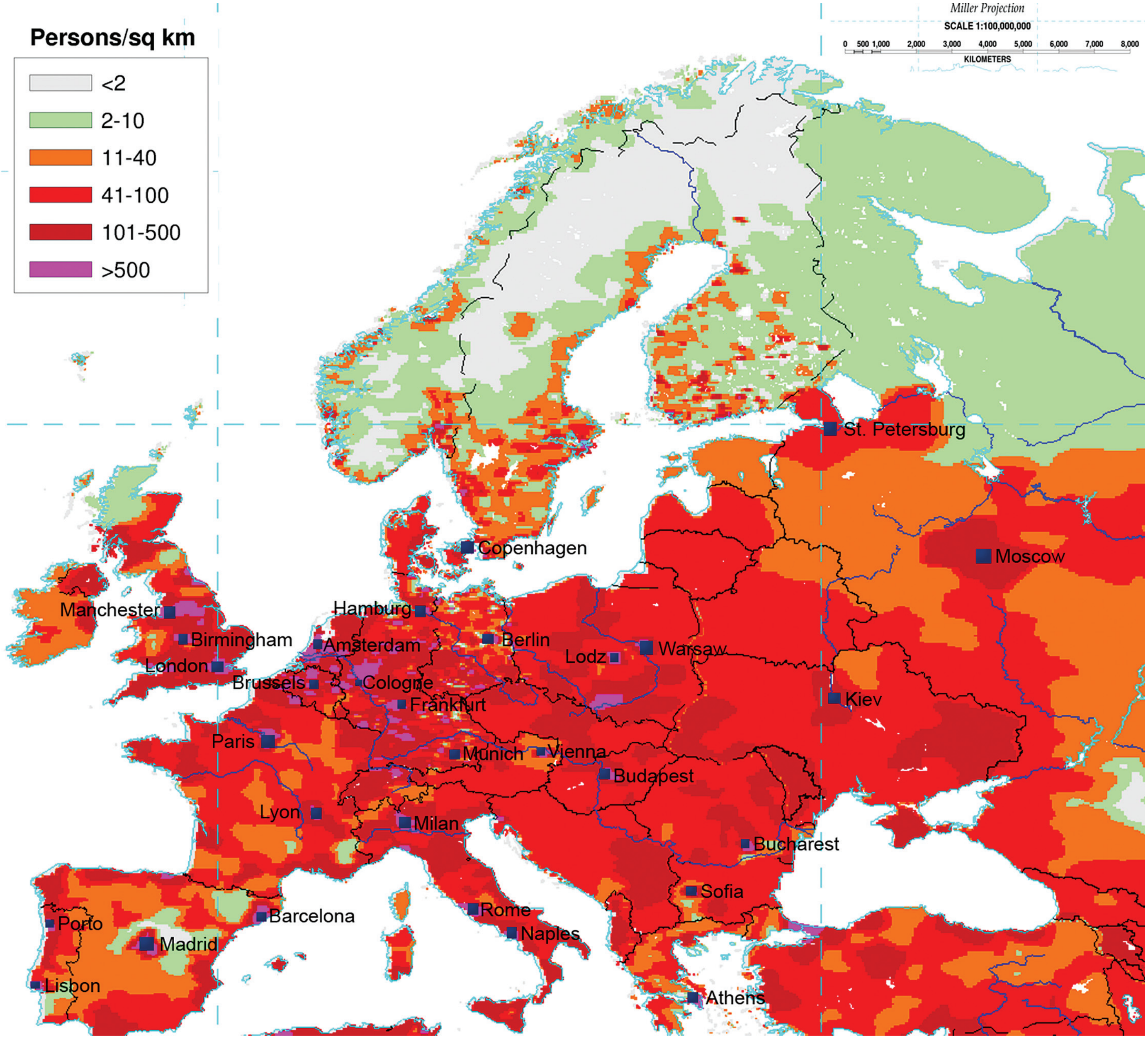

Figure 12.1 European population density and the location of major cities.

but with many small business areas. At the same time, it may reflect that people mainly live in dense suburbs and travel to work in a rather small downtown area. All these factors would directly influence the air quality in this city and consequently pattern of NO_x emissions and atmospheric concentrations.

Figure 12.3 illustrates another set of urban indicators. This shows, for example, that only 0.01% of wastewater was treated in Bucharest in 1999! Hopefully the situation has changed since then, because with 20% waste incinerated, the rest was deposited in open dumps. Obviously, the emissions of N_r into the water would be very high in this case.

Based on Figure 12.2, some medium-sized German and French cities of the lower left corner of the diagram such as Marseille and Lyon appear to be more sustainably managed than other cities shown. Lyon has a medium-sized population, low urban density and 100% of its wastewater is treated, while most of the solid waste is incinerated and only 4% properly land-filled, with some recycling taking place as well. While these indicators do not specify the efficiency of the water treatment and incineration plants, it is notable that Lyon also has a well developed public transport system combining buses, metro, funiculars and tram lines. The picture is of a city with a carefully organised infrastructure having the potential to reduce N_r emissions to air and water.

When dealing with urban transportation, not only the average urban density and the geographical expanse of urban areas are important, but also the differences in internal population density, i.e. density gradient. The average urban density data could mask significant variations within urban areas. For

Table 12.2 Mean travel time to work as an indicator, reflecting internal urban density gradients for selected European cities and areas (year 1999)

City	Country	Mean travel time to work (in minutes)
Amsterdam	Netherlands	22
Athens	Greece	53
Copenhagen	Denmark	22
Glasgow	United Kingdom	32
Hertfordshire	United Kingdom	27
Koeln	Germany	32
Lyon	France	32
Paris	France	35
Stockholm	Sweden	35
Donetsk	Ukraine	51
Minsk	Belarus	51
Moscow	Russian Federation	62
Nizhny Novgorod	Russian Federation	35
Tbilisi	Georgia	70
Yerevan	Armenia	52
Belgrade	Serbia	35
Bucharest	Romania	78
Budapest	Hungary	40
Prague	Czech Republic	57
Riga	Latvia	27
Sofia	Bulgaria	35
Warsaw	Poland	34
Zagreb	Croatia	26

Source: UNCHS Global Urban Indicators Database (2003).

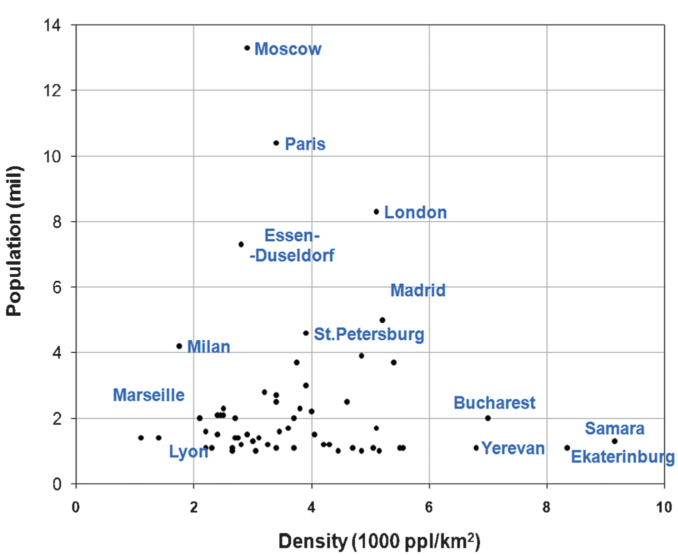

Figure 12.2 Population size versus density for the European cities of 1 million people or more.

example, London and Athens have similar population densities; however the core (central business district) densities in Athens are considerably higher than in London. The Athens suburbs, however, are among the least dense in the world. Similarly, the Essen-Dusseldorf and Milan urban areas have almost identical densities, yet core densities are considerably higher in Milan. This is because with the geographical expanse of nearly all modern, high-income urban areas, automobiles provide by far the greatest coverage, with considerably shorter travel times than public transport. For example, automobiles account for 88% of travel in the Essen-Dusseldorf urban area and somewhat more than 77% in Milan, with its steeper density gradient. These gradients also play a central role when considering wastewater treatment, which is addressed in detail in the following section.

Urban density or structure has an impact on air quality and in turn on the health of urban residents. Results of one study (Ferreira *et al.*, 2008) indicate that although compact cities provide better air quality compared with dispersed cities, the former have greater exposures and thus a higher health risk, due to high population density. Urban density could clearly serve as some integral indicator that reflects the quality of life, including N_r pollution levels, in cities of different types. As already mentioned, many cities of lower middle 'cloud' in Figure 12.2 are expected to expand at a high rate in the next 50 years. Therefore, the direction they will move on a plot has important implications for the anthropogenic urban N_r emissions.

Comparing European sub-regions

One important difference highlighted by the comparison of Bucharest and Lyon, is that they are situated in Eastern and Western Europe, respectively. The UN sub-divided the world according to the economic developmental stage and, as expected, the difference between Economies in Transition (ET) and Highly Industrialised (HI) countries within Europe is clearly reflected in the urban densities.

When comparing total urban areas and populations in cities of the two regions, we can see that ET exceed the values of HI region by two to six times, and that European cities have in general lower density than cities of Russia and Eastern Europe. For cities of half a million or more, Western Europe has an average urban density of 3150 inhabitants per km^2; Western Europe outside the UK – 3000; UK – 4100; Europe except Russia – 4200; Russia – 4900 (Demographia, 2009).

12.3 N-fluxes and city sub-systems, including a case study of the Paris Metropolitan Area

Cities show symptoms of the biogeochemical imbalances that they help to create. In urban systems, additional N inputs occur primarily via the importation of foodstuffs for humans, as well as by inadvertent 'fertilisation' through the production and subsequent deposition of NO_x derived from the combustion of fossil fuels. Cities also experience high acid deposition.

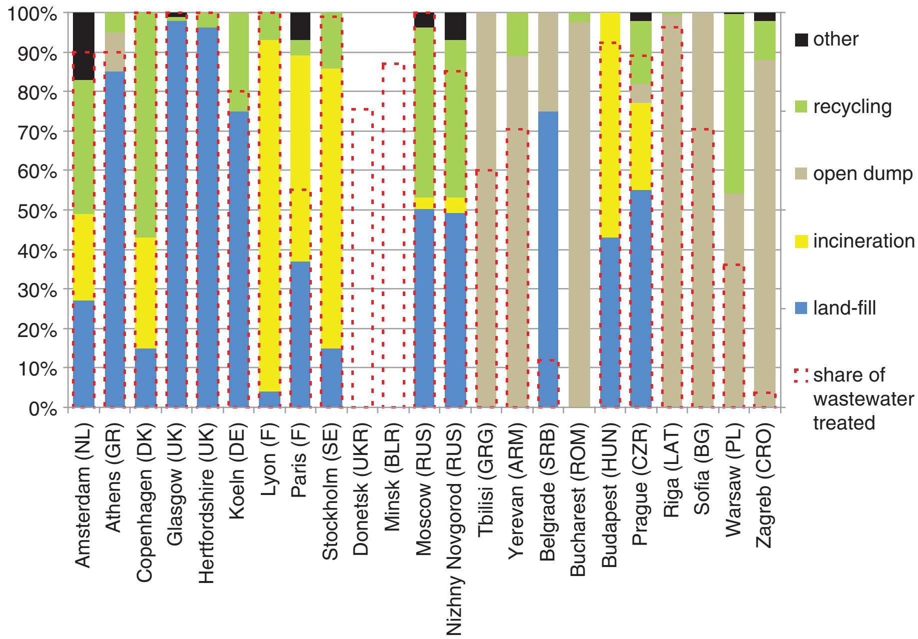

Figure 12.3 Liquid and solid household waste indicators for selected European cities for the year 1999. A substantial share of wastewater is treated in the majority of the cities listed (exceptions are Zagreb, Belgrade and Bucharest) and the level of land-filling is quite diverse among Western European cities, whereas open dumps are frequently used in Eastern and South-Eastern Europe.

Nitrogen transfers in human-dominated ecosystems are inherently inefficient; there is leakage of N at each point of the food chain from fertilisation through human excretion. These leaks could lead to increased storage in soil and groundwater pools and losses to rivers.

Air pollutants are transported over both short and long distances (as far as a few thousand kilometres) before being deposited on surface water, vegetation or soil (Bobbink, 1998). In this way, vegetation over a large area or in remote regions can be influenced by airborne pollutants (see Fowler *et al.*, 1998; Asman *et al.*, 1998). Elemental mass balances can frame this problem, because they identify potential excesses of inputs over outputs and likely sinks within the urban landscape (Baker *et al.*, 2001). Usually cities are hotspots of accumulation of N, P, and metals and, consequently, harbour a pool of material resources. By constructing mass balances at scales from the household to the city, human choice can be linked directly to biogeochemical cycling (Kaye *et al.*, 2005).

The following sections describe the general functioning of city sub-systems and development of the urban N budget for the Paris Metropolitan Area (PAM). They provide a view of the region's history, current status and projected impacts of N accumulation in adjacent areas, which generally has caused negative impacts. The N budget serves as a planning tool that is based on the estimation of gross N contributions from different N sources/components of the N cycle entering the system, as well as the amount of N leaving it. Such an analysis illustrates the spatial heterogeneity in both N_r creation and distribution of N from a local to a regional scale. The relatively simple N budget for Paris provides an assessment of the relative contributions of sources and the potential benefit of changes of management practices in the PAM. The subsequent sections (Sections 12.3.3 to 12.3.6) discuss urban N fluxes in a more regional context, supporting the statements of the case study for the PAM.

12.3.1 A case study and its historic development

The Paris Metropolitan Area occupies the Île-de-France, the geographic region constituting the lowland area around the city. This area, which forms the heartland of France, is drained largely by the Seine River and its major tributaries converging on Paris. The natural vegetation of the basin, broad-leafed deciduous forest biome, has been almost entirely lost to civilisation, except for a few relict forests.

In order to emphasise what is happening in urban areas concerning N it is relevant to go back as far as the end of the eighteenth century. Paris, an old European capital, is a good illustration, since some major historical changes occurred before 1950, while recent decades have been characterised by an unprecedented amplification of those changes. The population of Paris has dramatically increased since the beginning of the nineteenth century (see Figure 12.4).

Paris at the end of the eighteenth century and beginning of the nineteenth century already represented a substantial hub of N_r flows. The concentration of humans and animals (especially horses) in the city is estimated to have required an input of N_r of 24 g per head per day to meet the combined dietary needs. Material from cesspools and other organic matter placed in the streets came from households, animals, butchers, slaughterhouses and other industrial activities.

As a result of waste infiltration through the surfaces, the content of N_r in soils and underground water was high, for example the nitrate content in water from Paris wells was up to 2.2 g/L (Boussingault, 1858). Household water supply was nearly non-existent, but the river Seine was more or less preserved from human excreta discharge. This was however not the case for small industrial rivers (like the Bièvre in Paris) where water quality was poor.

Much of the N was recovered from the city waste, with urine and 'night soil' being collected in carriages and transferred to

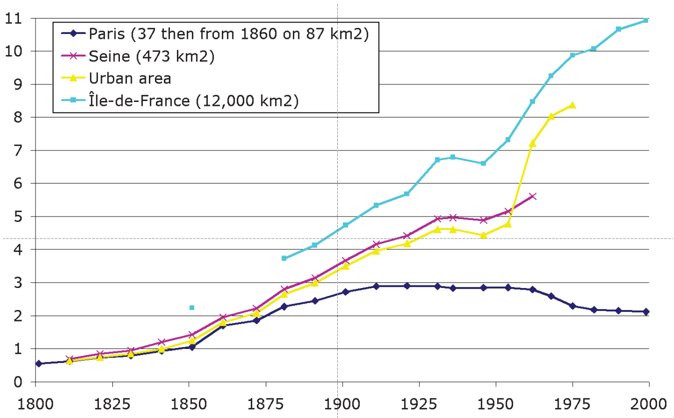

Figure 12.4 The human population of Paris, of the Seine catchment, of the urban area of the Seine and of the whole of the Île-de-France region, 1801–1999 (millions of people).

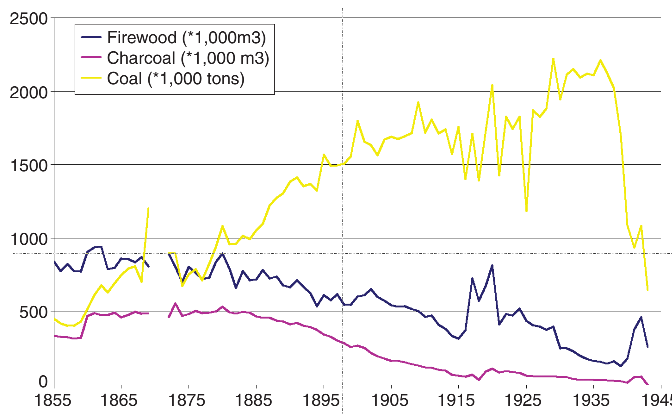

Figure 12.5 Firewood, charcoal, and coal consumption, Paris, 1855–1943.

the city refuse depots to obtain the N_r rich urine fraction and a phosphate rich fertiliser powder '*poudrette*'. The latter also contained significant amounts of N_r, though much less than the liquid fraction, especially as part of the N_r was volatilised as ammonia during its preparation (Barles and Lestel, 2007). Wood and, to lesser extent, coal combustion were responsible for emissions to the air – to these emissions of N_2O (from local denitrification) would have been added, although the latter can be considered as having a much smaller scale. Overall, the main urban impact on the N cycle at that time was in the form of underground accumulation, riverine discharge and emissions to the air.

The next stage of Paris's evolution was from the mid nineteenth century to the beginning of the twentieth century. The rates of human and animal concentration in cities kept increasing with more people moving in. Food production therefore became a central issue and so did the greater needs for fertilisers. From the 1820s onwards, cities came to be recognised as sources of fertilisers and the main concern was N recovery. There were many discussions between Boussingault and Liebig about this issue. As Jean Baptiste Dumas said: '*one of the most beautiful problems in agriculture lies in the art of obtaining nitrogen at low cost*' (Dumas, 1844, as translated by Barles and Lestel, 2007). In addition to the production of *poudrette*, from the 1830s, ammonium sulphate was manufactured in Paris using urine, and many patents involving the use of human manure and dry fertilisers were developed all around Europe.

The processing of N_r rich waste was particularly well developed in Paris (Barles and Lestel, 2007). Thus by the late nineteenth century around 50% of the city's excreta was collected and industrially processed. The excreta were settled and the *eau vanne* distilled industrially to produce ammonia (Vincent, 1901). Using the Margueritte process, the yield was estimated at 2.5–3 kg NH_x-N per m^3 of *eau vanne* (Vincent, 1901, p 6 ff, p 19). Based on these estimates, this would have amounted to around 800 000 tonnes of excreta processed industrially every year, from which around 2000 to 2400 tonnes of ammonium N were produced, mainly as ammonium sulphate. Combined with the processing of excretal solids to produce *poudrette* and other fertilisers, N recovery rates increased, but not enough to counterbalance the effect of urban population increase in the inner city and suburbs.

Water supply to households had been very much improved, but the question still remained of what to do with the water once used. Untreated wastewater provided a major source of pollution to the River Seine, with both high organic matter and ammonium content. Energy consumption (heating systems, gas production, industrial development) continued to increase. Coal progressively replaced firewood and was used either directly or turned into gas, causing the increase in related emissions (see Figure 12.5).

By the start of the twentieth century a major change occurred with the rapid growth of the household water supply, the introduction of British-style flushing toilets and the development of the piped sewage system, to which 10% of the population was connected in 1895 and 70% by 1914 (Barles, 2007). Flushing toilets produced much more dilute sewage streams, which were supplied as a liquid fertiliser to surrounding agricultural land. However, industrial processing of dilute sewage was much less cost-effective, and this was therefore a major factor contributing to the obsolescence of the system of recycling the N_r containing wastes (Barles, 2007; Barles and Lestel, 2007). Thus, by 1913, the production of ammonium sulphate from sewage was already down to 600 tonnes of N (Barles, 2007), substantially less than that estimated above for the turn of the century.

Between the beginning of the twentieth century and the 1970s, Paris grew as a source of N emissions to the water and air. The human population continued to increase in Paris, while the city sprawled over an even bigger area. However, the animal population decreased substantially. As horses were moved out of the city, total per capita N_r inputs decreased, yet consumption patterns and higher living standards still caused an increase in human N_r inputs, since a larger fraction of food was not eaten and contributed to waste. Table 12.3 shows these changes.

New sources of industrial N_r fertilisers were discovered, such as the Haber–Bosch process (Smil, 1999; Erisman *et al.*, 2008). During the first half of the twentieth century, the cheaper costs associated with this process removed the immediate need to use sewage N_r as a fertiliser. In time, N_r fertiliser manufacture from the excreta of Paris became completely uneconomic, so that by the 1920s, the industry was effectively at an end;

Table 12.3 Main characteristics of dietary nitrogen balance, Paris, 1817, 1869, 1913, 1931 (Barles, 2007)

	1817	1869	1913	1931
Human population	716 000	1 840 000	2 893 000	2 885 000
Horses population	16 500	50 000	55 000	10 000
Food inflows (Gg N)	6.0	17.6	23.5	19.7
Urban fertiliser produced				
Street sludge (Gg N)	0.5	1.3	2.1	0.7
Horse manure (Gg N)	0.6	1.8	1.8	0.4
Human manure (Gg N)	0.1	1.1	1.2	0.1
Wastewater to sewage farms (Gg N)	0	±0[a]	4.0[b]	4.0[b]
Total outflows to agriculture (Gg N)	1.2	4.2	9.1	5.2
% of food inflows	20	24	40	26
Direct discharge to Seine (Gg N)	?	?	3.1	7.0
% of food inflows	?	?	13	36

[a] A substantial fraction of the sewage was processed industrially for ammonium sulphate production (Vincent, 1901).
[b] This concerns only the dietary nitrogen. The total amount of nitrogen in wastewaters is more important.

Table 12.4 Sewage treatment capacity increase for the growing population (Billen *et al.*, 2009)

Year	Rate of connection to sewage collection system (%)	Installed domestic wastewater treatment capacity (inhabitant equivalent)
1954	9	300 000
1962	18	500 000
1971	23	2 000 000
1976	31	4 900 000
1980	38	7 200 000
1985	50	9 600 000
1991	60	9 700 000
1996	70	11 300 000

urban N_r, which had been a previously valued product, became a waste product for disposal. Wastewater treatment plants were thus constructed, focusing on removing nitrogen through denitrification, which gradually increased their treatment capacities (see Table 12.4).

Surface water contamination continued to increase during this period, since the environmental issue alone (the agricultural pressure disappeared) was not important enough at that time to provoke water treatment enhancement. As heavy industry was moved out of Paris, emissions from industry (industrial N and other pollutants) became distinct from those generated by other urban processes. This, however, did not mean that industrial N emissions decreased, but rather that urban N emissions to the air became impacted by energy transitions. On the one hand, they decreased because of the increased share of electricity in the energy system (which was earlier dominated by gas produced from coal or coal itself). However, urban N emissions decreased substantially only with the construction of nuclear power plants or even since coal power plants were taken outside the city. At the same time, emissions to the air increased as fuel-powered transport replaced horse transport and overall traffic increased due to urban sprawl.

From the 1950s the use of N_r fertilisers increased substantially. The mean application rate was 13 kg N per ha/yr on agricultural land in France, which thus increased to 114 kg N per ha/yr in 1996. While ammonium in the River Seine was practically undetectable before the middle of the 1960s, the maximum contamination was reached during the 1970s, owing both to increased urban population (mostly in the downstream part of the sub-basins, as a result of the expansion of the Paris agglomeration) and to increased rates of sewage collection, often released into surface water without treatment. However, later on progress in wastewater treatment led to a considerable decrease in ammonium contamination during the 1990s (Barles, 2007).

12.3.2 Nitrogen budget for the Paris Metropolitan Area

The urban nitrogen budget (balance) can be considered as a subset of national and regional N budgets. It incorporates imports of N_r-containing products into the city, their conversion within the city boundaries and exports outside of the urban sphere. The urban sphere incorporates the three dimensional space surrounding the urban habitat and spans all environmental media, water, air and soil.

We make the first step by creating a detailed N_r mass balance for Paris and its urbanised surroundings in order to estimate the magnitude of major fluxes across the urban landscape and to see how N cycling varies among urban system components. This will help to determine which budget terms are most open to management efforts to reduce N pollution to recipient systems. The budget is shown in Figure 12.6.

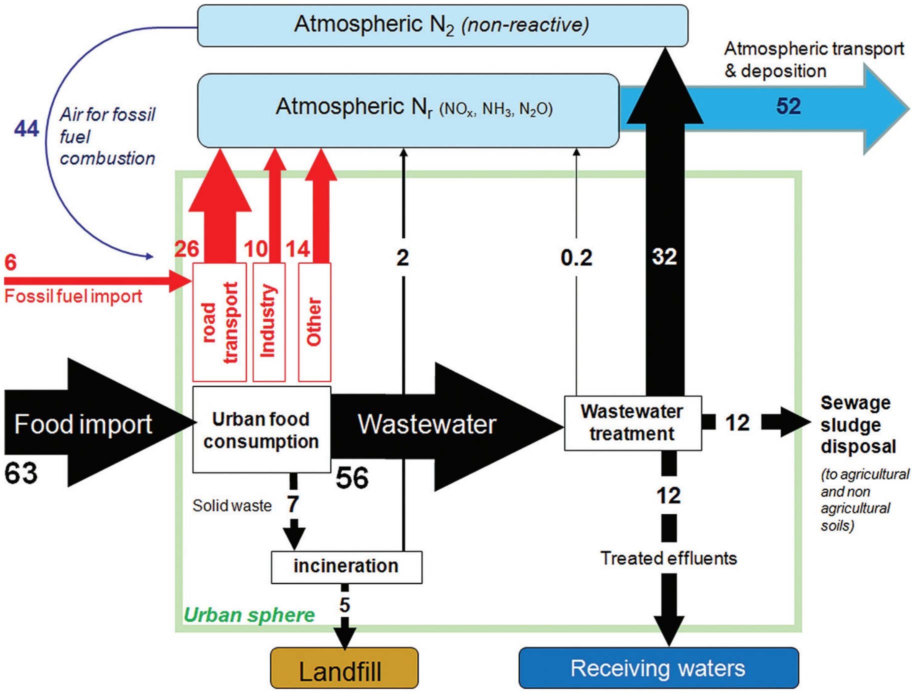

Figure 12.6 Nitrogen flows quantified for the Paris Metropolitan Area for the year 2006 (PAM, numbers in Gg N per year). The quantified fluxes displayed reflect major N flows through the PAM originating from food import and fossil fuel use, as well as N_2 out-flux from wastewater treatment.

Notes: The calculation of fossil fuel input has been based on total gasoline consumption for France, weighted by the urban population of the Paris Metropolitan area. Rough assumptions had to be made regarding gasoline N content, fuel N conversion rate in combustion and that the average per capita consumption for France was a suitable indicator for Paris. In reality, it is likely that the urban population will rely more on public transport and this figure may be an overestimation, however, it indicates that the bulk of emissions from fossil fuel combustion stem from N_2 conversion of air N content in the combustion process, whereas the fuel N contribution is comparatively small. It has to be stated as well, that this figure only covers gasoline consumption, which is assumed to be the largest contributor of fossil fuel N_r import into the city.

The dry and wet deposition of N_r on the soils and surface waters of the PAM were not quantified due to a lack of modelling results for this specific spatial domain. Considering a total emission to air of approx. 50 Gg N per year, dry and wet deposition may lead to a substantial contribution to nutrient input into urban soils and waters.

If solid waste has been thermally treated, the remaining N_r content of the waste deposited in landfills should be negligible. Because of the relatively low temperatures at which municipal waste furnaces operate, 70%–80% of NO_x formed in municipal waste furnaces is associated with nitrogen in the waste and is emitted to air, alongside small amounts of NO_2 and N_2O (in particular from emission control equipment for flue-gas treatment of incineration plants).

Emissions of nitrogen containing species (mainly NH_3) from untreated municipal waste in landfills due to rotting and chemical conversion processes are difficult to quantify, as they depend on the content of the waste stored, moisture and other parameters. In most cases, only CH_4 emissions from landfills are monitored and used for power generation. Overall, based on Sutton *et al.* (2000), volatilisation emissions of NH_3 in the PAM may be of the order of 1–2 Gg N_r per year.

The estimates in this figure are derived from the mass balances of urban food consumption and nutrient flows (Faerge *et al.*, 2001; Magid *et al.*, 2006), data on N_2O emissions from wastewater treatment plants (Thomsen and Lyck, 2005) with the focus on the urban sub-systems. Obviously, the urban consumption of resources produced elsewhere (notably food) gives rise to substantial leakages of N_r, and should be included in an ecological footprint analysis, as in Rees (1997) and Wackernagel and Rees (1997).

Based on the indicative calculation illustrated in Figure 12.6, the Paris Metropolitan Area is a source of N_r, emitting in total the amount of 50 Gg per year to the atmosphere, the major part being attributed to the emissions from transport and energy. Although much smaller, emissions of N_r to air from the incineration of solid waste are also substantial, contributing 2 Gg per year.

The amount emitted to the aquatic environment, at about 12 Gg N/yr, greatly depends on the type of wastewater treatment adopted. Disposal of solid wastes and incineration residues in landfills or of sewage sludge on agricultural and non-agricultural soils (potentially leaking to the ground water over time), together amount to 17 Gg N/yr.

Regarding the transformations between N_2 and N_r, the largest of these occurs outside this budget, in the production of fertiliser N_r to provide food. Overall, the food N_r import of 63 Gg per year is of a similar order of magnitude to the inadvertent fixation of N_2 to N_r through combustion processes. However, the fate of the N_r produced by the two processes is very different.

In the case of N_r in food, most is transferred to waste waters, with over half of this being denitrified to N_2 in wastewater treatment, i.e. 32 Gg, with only around 0.2 Gg per year being emitted as N_2O (Tallec *et al.*, 2007). Although NH_3 volatilisation from wastewater treatment is unquantified, based on UK estimates (Sutton *et al.*, 2000), it is expected to be similar at around 0.2 Gg per year. As a result of the major loss by denitrification, this leaves only around 12 Gg per year which is returned to agricultural and non-agricultural land, with 12 Gg per year of N_r lost to the environment in receiving waters. The small fraction of the food import N_r being reused on agricultural and non-agricultural land of 20%, compares with a value of nearly 40% achieved in 1913 (Table 12.3).

In the case of N_r from combustion processes, effectively all of this is exported from Paris as N_r. Thus four times as much N_r is released to the environment of Paris from combustion processes than from the N_r originating in food imported to Paris. If this highlights the problem of N_r emissions from combustion sources for this city, it should not be forgotten that the N_r denitrified in wastewater treatment represents the loss of a valuable resource. Without commenting here on the economic viability of recycling wastewater N_r, it may simply be noted that, at an indicative value of €1 per kg fertiliser N_r, the denitrification of wastewater N_r in Paris represents an annual resource loss of €32 million per year.

12.3.3 Human food sub-system

An important criterion for the assessment of a city's functioning in relation to the N cycle could be set as the relation between urban population growth and rural productivity (nitrogen-containing food products). In other words, is there enough land surrounding a city to feed its population and how does its rate of growth compare to the growth rate of the urban population? The concept of the so-called food print has been suggested by Billen *et al.* (2009) and discussed in the previous sections. However, this is not a simple relation, since the amount of land could remain the same while its productivity increases due to the introduction of new technologies based on artificial N_r fertilisation, etc. The food could also be imported. This is precisely what caused the food print of Paris to shrink during the second half of the twentieth century, while its population dramatically increased, eventually reaching 10 million inhabitants.

Inputs to the human food system include imported and internally produced food, while outputs consist of discharges of unutilised food to landfills and excretion to wastewaters. The size of the area that feeds Paris remained more or less the same and corresponds to the Seine watershed being around 60 000 km^2. However, if we look at the ecology of a city, we also need to be sure that water and air pollution do not impair the hinterland surrounding it, thus making the lands less productive.

The average intake of protein by the population of the EU is 105 g per person per day, while for France this value is 118 g per person per day, one of the highest in the world (FAO Nutritional Studies). Based on this figure, for France the total direct human consumption of nitrogen is 420 Gg N_r per year, corresponding to about 14% of total EU human consumption of protein. Consequently, for the Paris Metropolitan Area it should be 79.9 Gg N per year. Most food protein is contained in animal products, the common protein sources for Europeans being meat from pigs, cattle and poultry and eggs (FAO Yearbook, 2005/2006). Normal well-fed adults exhibit a nitrogen balance where N_r ingested equals N_r excreted (Voegt and Voegt, 2003), therefore 100% of the outputs from the human food sub-system enter directly into the wastewater subsystem. In other words, human direct consumption should be about the same as human direct excrement to the wastewater subsystem. However, for the mass balance calculations presented earlier in the text, we modified the figure to 63.3 Gg N per year based on Magid *et al.* (2006), who estimated the annual production of nitrogen per person to be 6 kg, of which 0.37 kg is from detergents and the like used in washing water. The rest is related to food intake, either directly or to the food waste going to the bin or kitchen sink.

12.3.4 Sewage system: N in liquid and solid fractions of urban waste

The main point sources of nitrogen in discharges are human or industrial sewage treatment plants, larger agricultural units (husbandry) and, of course, untreated wastewater from urban areas (Figure 12.7).

In Western Europe, population increased from 466 to 519 million inhabitants (+11%) between 1970 and 2000, which is a slower growth than in North America, for example. Human N_r in sewage increased from 4.8 to 5.7 kg per person per year in the period 1970–2000. Similarly, human P emissions increased from 0.8 to 1.0 kg per person per year, while detergent P emissions decreased from 0.3 to 0.2 kg per person per year, with a peak in the 1980s (Van Drecht *et al.*, 2009) . In 1970 about 64% of the population of Europe was connected to sewage systems, increasing to 79% in 2000; in the same period the amount of N removed in wastewater treatment (as denitrification to N_2) increased from 10% to 50% of the N_r and P removal from 11% to 59% (Van Drecht *et al.*, 2009). The sum of all these changes was a slight decrease of the N_r discharge to surface water (after treatment) from 1326 to 1192 Gg/yr (Figure 12.8); P discharge to surface water decreased from 333 to 216 Gg/yr. Hence, despite the enormous investments in the construction of sewage systems and wastewater treatment facilities, the N_r flow from households to surface waters is still considerable. With higher P removal rates the flows of P are reduced more effectively.

For Europe, nitrogen discharge has become an important issue, when in the mid 1970s massive recurrent blooms of gelatinous *Phaeocystis flagellata* (producing toxins that kill marine animals) colonies and cells were observed each spring in the coastal areas of the North Sea. Practically all investigators came to one conclusion: the change of dominance from diatoms to *Phaeocystis* was a consequence of the nitrate enrichment of coastal waters in response to the cumulative nutrient discharges by the major North-West European Rivers, and especially of the decrease of Redfield ratio due to the abundance of phosphorus in the input flow of biogenic pollutants. A detailed description of the precise spatio-temporal interactions between human activities and the functioning of river basin ecosystems and estuaries is presented in Billen *et al.*, 2011 (Chapter 13, this volume).

The urban sewage treatment process is primarily designed to reduce the level of pollution of watercourses by organic matter, which results in the oxidation of nutrients to inorganic forms. Technologies of nutrient removal are relatively new: 'tertiary treatment' normally follows the normal two-stage treatment of sedimentation, followed in turn by biological treatment. These technologies allow most of the N_r and phosphorus to be removed. But the costs of removal grow very fast according to the degree of cleaning required.

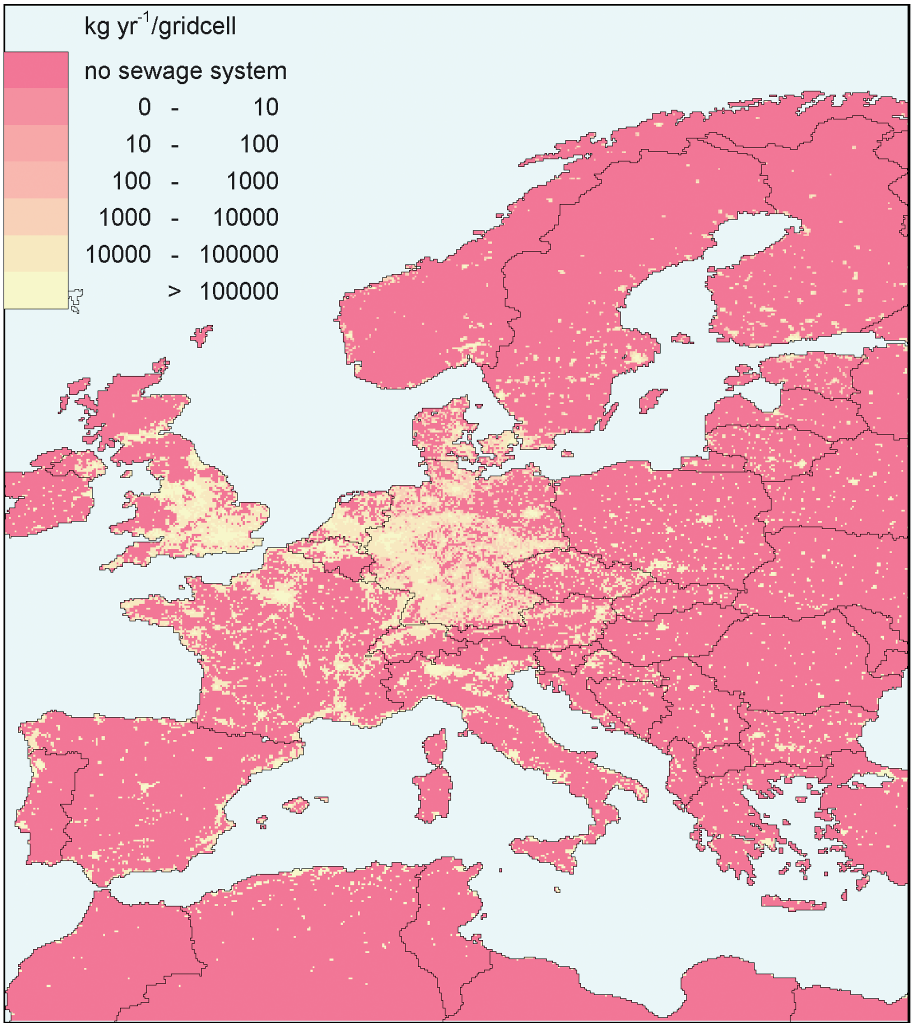

Figure 12.7 N effluent from sewage systems after wastewater treatment for 2000 for Europe (based on data from Van Drecht *et al*., 2009).

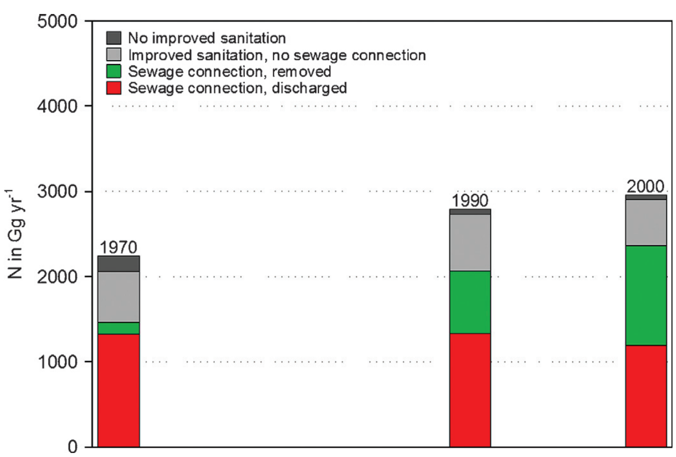

Figure 12.8 Trends in human N emission by type of sanitation, sewage and N removal for 1970, 1990 and 2000 for Europe. Improved sanitation indicates N from households with connection to public sewerage, but also to other systems such as septic systems, simple pit latrines, pour-flush, and ventilated improved pit latrines. It is assumed that the N from households with no improved sanitation or with no sewage connection does not end in surface water. Therefore, the N from households and small industries that enters the surface water is the N from sewage systems with no treatment or after treatment (the red parts of the bars). Figure based on data from Van Drecht *et al.* (2009).

Traditional wastewater treatment can remove 85%–95% N_r and 90%–95% phosphorus. The operational cost is around 1€ per kg nitrogen removed (i.e. denitrified to N_2) and 1.5€ per kg phosphorus removed. Construction cost is at a similar level. In principle, up to 100% of N and 90% of P can be removed from wastewaters, but these are very expensive technologies (Henze *et al.*, 2008).

The nitrogen in wastewater is, in general, in the form of ammonia, also some nitrite is present in low concentrations, but both are toxic for fish. Most technologies use a two-step process: nitrification (ammonia → nitrate) and denitrification (nitrate → gaseous nitrogen). Usually, combined treatment plants are used, where nitrification and denitrification occur in different zones controlled by oxidation. For instance, the 'Carousel' system allows up to 50%–70% removal of the total nitrogen. Certainly, physical and chemical processes exist for ammonia removal, although they are more expensive than the microbiological ones. Chemical stripping by the addition of lime (so that the pH of the sludge rises above 11), and further passage of it through an aeration tower can raise the degree of removal up to 90% (Hammer and McKichan, 1981). In some areas septic systems (installed in allotments and suburban residences) are suspected of causing an increased level of ground-water contamination. Intermittent loading or recycling of nitrified effluent are suggested as methods of improving denitrification in septic systems. This becomes especially relevant in view of the growing suburbanisation of Europe.

These days, European cities usually direct all their wastewaters to treatment plants, however in the 1980s and 1990s the situation was very different, especially for the Eastern European countries (see Figure 12.3): in Bucharest, for example, only 0.01% of wastewater was treated, in Belgrade 12% and in Warsaw 36%.

Since then, the Urban Wastewater Treatment (UWT) Directive was issued in 1991, which regulates wastewater treatment in Europe. It requires the collection and treatment of wastewater in all agglomerations of >2000 population equivalents, p.e., (where 1 p.e. is the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day); secondary treatment of all discharges from agglomerations of >2000 p.e., and more advanced treatment for agglomerations >10 000 p.e. in designated sensitive areas and their catchments. The UWT Directive requires the pre-authorisation of all discharges of urban wastewater, of discharges from the food-processing industry and of industrial discharges into urban wastewater collection systems; it moreover monitors the performance of treatment plants and receiving waters and controls the sewage sludge disposal and reuse, and treated wastewater reuse whenever it is appropriate.

Sewage water reuse is one of the adaptation strategies listed in the IPPC 4th Assessment Report for the water sector (IPCC, 2007). Segregated wastewater collection enables efficiency in reuse of water and the nutrients found in wastewater. Consequently, water resources are conserved and nutrients are returned back to the soil. In this system, greywater and blackwater are collected separately from urban households. Rainwater is also harvested before it reaches wastewater collection systems.

The UNDP Environment and Energy Program defines *Ecological Sanitation* (ECOSAN) as '*an approach to human excreta disposal that aims at recycling nutrients back into the environment and productive systems*' (see further discussion by Oenema *et al.*, 2011, Chapter 23, this volume). Ideally, a community using the ECOSAN approach disposes no raw or treated wastewater into the water bodies, limiting the disposal of xenobiotics, including endocrine disrupting chemicals (EDCs), pharmaceuticals and personal care products (PPCPs) along the way.

It should be noted that this approach cannot be applied to urban areas with established centralised wastewater collection and treatment systems. However, this is easily adoptable in newly developing urban settlements. Strict legislation is lacking, however, the World Health Organization (WHO, 2006) has issued 'Guidelines for the Safe use of Wastewater, Excreta and Greywater'.

Greywater is rich in terms of phosphorus but the nitrogen content is limited (Atasoy, 2007). Urine contains approximately 80% of the N_r and 55% of the phosphorus found in domestic wastewater (Leeming and Stenstrom, 2002). As was already mentioned, in conventional treatment systems, nitrogen and phosphorus are removed in tertiary treatment. Sludge, containing some of the remaining nutrients, is then disposed of most commonly either by landfill or incineration. With segregated water collection, on the other hand, water is reused and nutrients are returned back to the soil as fertiliser.

Table 12.5 Nitrogen emitted from wastewater treatment for all European cities of over 1 million, contrasting a scenario of current water treatment (80% treatment, with denitrification based approaches) with a system of latrine water recycling; based on per capita recalculations (Magid *et al.*, 2006).

Receiving media	N Gg per year 80% treatment	Gg N per year New system of latrine water recycling
Water (N_r)	157	26.2
Sludge (N_r)	157	52.4
Air (denitrified to N_2)	418	0
Recycled (as fertiliser N_r)	0	629
Total	**732**	**708**

One interesting historical example of the latrine sewage recycling, implemented in the middle of the nineteenth century in Copenhagen, is described in the Box 12.1. It also describes the situation in London at that time. Box 12.2 describes the beginning stage of centralised urban water management in Russia.

It is indeed possible to reduce the amount of N_r entering the surface waters substantially and to entirely eliminate N_r emissions to the atmosphere from wastewater treatment plants (Magid *et al.*, 2006). Figure 12.14 shows the scheme suggested for the recycling of sewage waters. It is relevant to estimate the total amounts of N_r in different fluxes for all major European cities (> 1 million population) using the traditional cleaning method and the suggested utilisation. Table 12.5 shows the calculated values, which clearly highlight the advantages of the proposed utilisation scheme. Overall the production of fertiliser in recycling N_r for major European cities would have the theoretical potential to produce over 600 Gg N_r per year, equivalent to around 600 million € per year, at the same time as reducing polluting losses to the environment.

Box 12.1 Urban waste management in the nineteenth century: London and Copenhagen

London

In 1840 Thomas Cubitt wrote '… Fifty years ago nearly all London had every house cleaned into a large cesspool …. Now sewers having been very much improved, scarcely any person thinks of making a cesspool, but it is carried off at once into the river. The Thames is now made a great cesspool instead of each person having one of his own …'. By then London had reached over 2 million inhabitants, and was the largest city in the world. Cholera outbreaks had begun some years earlier, but the cause for this was not understood. The main reason for public debate was caused by the stink of the Thames. This fired a debate on how to manage waste. At this time Justus von Liebig wrote a letter to the Prime Minister of the UK Sir Robert Peel.

..The cause of the exhaustion of the soil is sought in the customs and habits of the towns people, i.e., in the construction of water closets, which do not admit of a collection and preservation

of the liquid and solid excrement. They do not return in Britain to the fields, but are carried by the rivers into the sea. The equilibrium in the fertility of the soil is destroyed by this incessant removal of phosphates and can only be restored by an equivalent supply. …If it was possible to bring back to the fields of Scotland and England all those phosphates which have been carried to the sea in the last 50 years, the crops would increase to double the quantity of former years…'. In his book on *Agricultural Chemistry* (1862) von Liebig later stated that '*The introduction of water-closets into most parts of England results in the loss annually of the materials capable of producing food for three and a half million people; the greater part of the enormous quantity of manure imported into England being regularly conveyed to the sea by the rivers …like a vampire it hangs upon the breast of Europe, and even the world; sucking its life-blood*.

Although von Liebig focused his argument on phosphorus, it is clear that they applied just as much to N_r.

When London's authorities decided to construct a sewage disposal rather than a recycling system suggested by Liebig, he increased his effort to find ways to replace the fertility removed by cities from farmland by artificial means. He focused in particular on developing artificial fertilisers to keep the agricultural land productive in order to feed the cities.

Copenhagen

At around the same time as these developments Copenhagen was bankrupt. Similar problems with waste arose, although on a smaller scale and cholera outbreaks eventually visited Copenhagen in 1853. The future waste management system was hotly debated, but in the end the state prohibited sewers in 1858 due to insurmountable costs, and the city negotiated contracts with farmers for collection of latrine waste. Eventually this system was developed into an elaborate service industry that ensured timely collection and daily transport of latrine contents to the eastern and western outskirts of the city. Figure 12.9 shows show night soil workers empty stainless steel drums into large wooden barrels, and subsequently wash and steam rinse the drums. Furthermore they show farmers collecting night soil from the latrine wagons that were commonly known as 'The Royal Train' and 'The Chocolate Express' (see Figure 12.10). Cholera subsided during these years, and the hinterland farming community gained access to fertiliser as well as a growing market for perishable foods, resulting in better welfare. This system persisted until after the Second World War, but gradually gave way to sewers and water closets. Peri-urban farmers were strong stakeholders, protesting vociferously against the decline of the system and the resulting negative effects on their farmland productivity.

Figure 12.9

Figure 12.10

Box 12.2 The history of centralized water supply and canalisation in Moscow

There were no centralised systems of water supply for cities in Russia before the end of the nineteenth century. The water was taken from the streams and wells. Cities were supplied with water in barrels (fig. 12.11).

Figure 12.11 Water, brought to the city in barrel (Miksashevsky and Korolkova, 2000).

The domestic waste discharges were dumped in the nearby water body or just on the streets.

Therefore the water bodies were polluted and were the sources of infectious diseases. The canalisation systems were constructed earlier in Europe: first in London, then in Paris and Berlin. The positive results were immediate, like in Berlin in the course of one year after the centralised sewage system was built, the water quality was greatly improved and the number of people who contacted cholera dropped by half, and soon the disease was entirely eliminated.

With the growth of large cities and rapid increase of their inhabitants, the need for the centralised water supply developed. The late development of centralised water supply in Moscow, contrasted with the fact that smaller-scale water

Box 12.2 (*cont.*)

supply systems existed earlier in Eastern than in Western Europe. For example, the archeological findings suggest their presence on the territory of Caucusus, (Russia) Great Novgorod and Ukraine (see Figure 12.12).

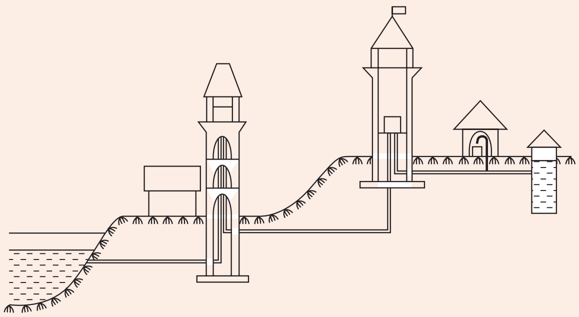

Figure 12.12 An example of small scale water supply: Kremlyn palace, Moscow (17th century).

The centralised large water supply system started to operate in Moscow in 1892, when the two main pumping towers were constructed (see Figure 12.13).

Figure 12.13 "Kretsletz" main water pumping towers.

In 1874, engineer M. A. Popov brought to the attention of the Russian government that sewage channels needed to be built in Moscow and suggested that sewage waters be removed from the city and purified using special irrigation fields (with later usage as fertiliser). Popov used his own funds for collection of topographic and soil data and made sewage application capacity calculations, based on fundamental population growth projections. He developed the entire project of combined sewage system and estimated the construction costs as well as costs of using sewage residue. Unfortunately, the implementation of an actual plan was delayed, due to disagreement with the external evaluator from Berlin, Gobrecht, who supported the plan at first, but then found some flaws and offered to take it over. In 1890, a segregated sewage system project, developed by the engineer Kastilsky, was implemented. By 1898, 262 km of pipelines had been laid and the main pumping station was built. By August 1899, the system began to function to distribute sewage waters to agricultural irrigation fields.

12.3.5 Urban N fluxes due to the combustion of fossil fuels in stationary and mobile sources

The main contribution to urban air quality problems is made by the combustion of fossil fuels. Emissions come from both stationary (residential and commercial combustion for heating and process water purposes, combined heat and power plants) and mobile sources (road and off-road transport and machinery). The general mechanisms leading to the formation of the most relevant pollutants (NO_2, NO_x, NH_3, ozone and secondary aerosols/particular matter are illustrated by Hertel *et al.* (2011, Chapter 9, this volume), which gives a detailed account of the processes leading from emissions to ambient concentrations.

Here, only specific aspects of urban air quality will be discussed. Kousoulidou *et al.* (2008) analysed the projections of road transport emissions until 2020 and state that while significant reductions are to be expected for relative emissions per vehicle and kilometre driven, NO_2 concentrations in urban areas are not expected to fall as dramatically. This is mainly due to the change in the NO_2/NO_x emission ratio of new technologies, aiming for instance to reduce PM emissions from vehicle exhausts (see also Keuken *et al.*, 2010). This trend will most likely have implications for the attainment of ambient air quality standards for NO_2 concentrations in all large European cities. Beevers and Carslaw's (2005) earlier work concluded this for central London. In addition to the technology changes in vehicles and control equipment, an increase in annual average mileage driven in urban areas may arise from a continuing urbanisation towards the development of urban sprawls, as discussed by De Ridder *et al.* (2008).

Stationary sources of emissions in urban areas are residential and commercial combustion plants on the one hand (household heating and process water, open fireplaces, etc.) and – with the deregulation of the energy markets and increasing fuel prices – decentralised small power plant units (in most cases combined heat and power, CHP, plants based on natural gas or renewable fuels, e.g. biomass) on the other hand. While solid fossil fuels have been banned for use in private stoves in some countries and regions/cities, they contribute a significant share of household heating especially in Scandinavian countries and Central and Eastern Europe.

The major contributing sources obviously vary from city to city, however a few patterns can be identified by looking at the information available from individual large urban areas in Europe, such as Greater London (Table 12.6) or Berlin (Table 12.7).

Table 12.7 illustrates the situation in Berlin, showing a bulk of NO_x emissions stemming from road transport sources. In contrast to Greater London, however, industrial emissions contribute a significantly larger share in Berlin with about 32% of facilities requiring a permit to operate, and thus being subject to regulation. Domestic fuel combustion makes up only about 11% of NO_x emissions in Berlin.

The above tables illustrate the relative contribution of major activities to urban air quality problems, namely high ambient concentrations of NO_2, ozone and particular matter. Figure 12.15 displays the percentage of the urban population in Europe experiencing pollutant concentrations above the respective target/limit values. A clear downward trend can be observed for SO_2 together with a less pronounced one for NO_2. Concentrations of NO_2 in general and population exposure to very high (>40μg/m^3) concentrations have declined in the 10 years between 1997 and 2006 (see Figure 12.16).

Table 12.6 Share of emissions within Greater London and on a national scale for the year 1999. This table illustrates the relevance of road transport sources for urban air quality and indicates a significantly larger proportion of nitrogen (58.2%) being contributed by urban road transport. Industrial sources, in contrast, play a minor role (8.9%) and only about 33% of urban NO_x emissions can be attributed to other sources

	Total emissions in Gg per year	percentage of emissions in Greater London		percentage of national emissions	
	All sources	Road transport	Industry	Road transport	Industry
Nitrogen oxides (NO_x)	**68.13**	**58.2**	**8.9**	**44**	**37**
Fine particles (PM_10)	2.75	67.9	22.3	20	44
Sulphur dioxide (SO_2)	3.55	38.3	39.1	1	89
Carbon monoxide (CO)	173.38	93.7	1.4	69	16

Source: Mayor of London's Air Quality Strategy 2010).

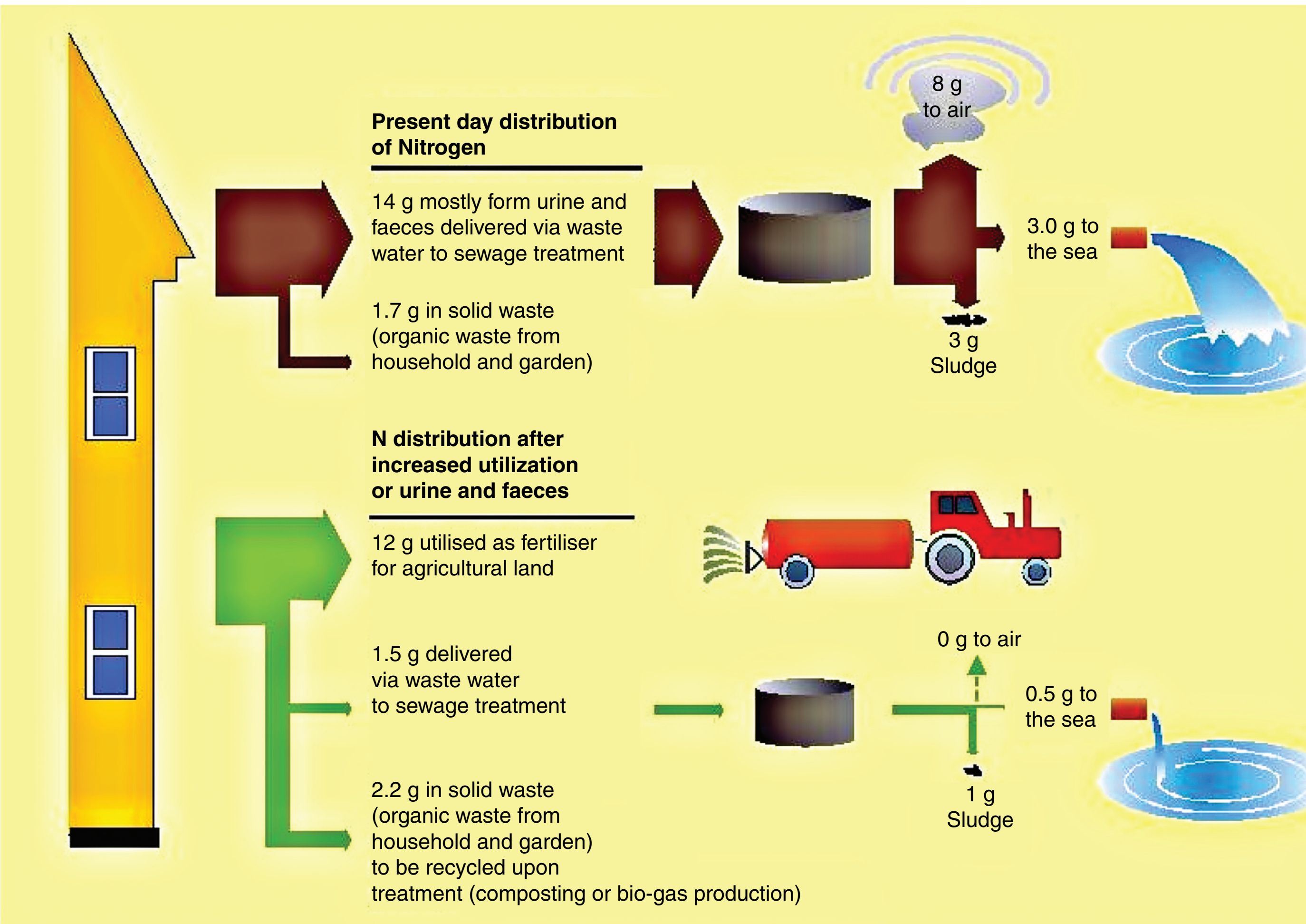

Figure 12.14 Current versus increased utilisation method of N distribution (g per capita) (Magid *et al.*, 2006).

At the same time as Figures 12.15 and 12.16 show the decline in exposure to high NO_2 concentrations in urban areas, a more frequent occurrence of exposures to high ambient levels of ground level ozone above 120 µh/m³ (8 h mean) are observed (Figure 12.17). It is difficult to assess to what extent this increase of exposure of the urban population to high ambient levels of ground level ozone is caused by urban emissions (resp. the reduction of urban NO_x emissions and the resulting decrease of the titration effect in NO_x-rich environments) and to what extent by the slowly increasing concentrations of global background ozone levels. In particular, exposure to high ambient concentrations of ozone and PM lead to adverse effects on human health, which are discussed in detail in Moldanová *et al.*, 2011 (Chapter 18, this volume).

Table 12.7 Emissions of NO_x in Berlin according to emitting groups (Gg per year)

	Data in Gg per year					
Nitrogen oxide	**1989**	**1994**	**2000**	**2002**	**Trend 2005**	**Trend 2010**
Germany	**2862**	**2226**	**1815**	**1640**	**1447**	
Berlin	**70.0 (2.4%)**	**42.4**	**26.1**	**22.1**	**19.8**	**17.5**
Emittent approved facilities	41.8	16.2	8.3 (*31.9%*)	6.5	6.0	5.8
Domestic fuel	2.7	3.1	2.9 (*10.9%*)	2.9	2.7	2.6
Small trade	1.2	0.7	0.2 (*0.7%*)	0.2	0.2	0.1
Traffic (*motor vehicles only*)	21.4	19.0	12.4 (*47.5%*)	10.5	8.9	7.0
Traffic (*other*)	1.4	1.3	1.1 (*4.3%*)	1.1	1.1	1.1
Other sources	1.5	2.1	1.2 (*4.6%*)	1.0	1.0	0.9

(Source: Senate Berlin, 2010).

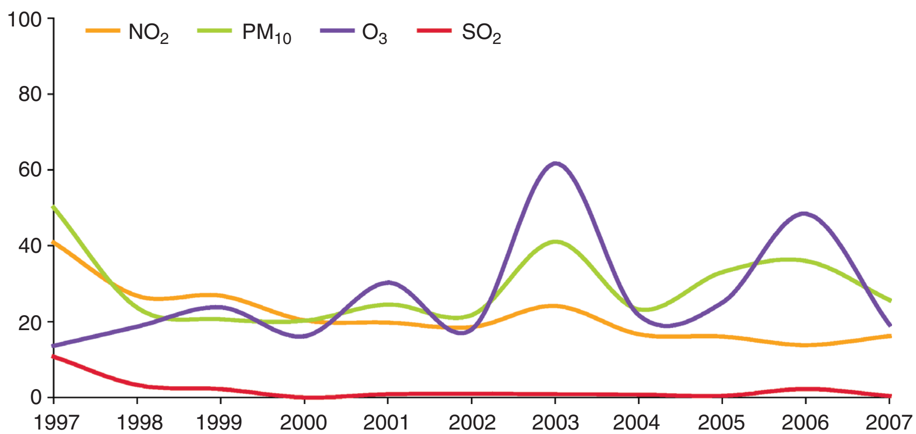

Figure 12.15 Percentage of urban population resident in areas where different air pollutant concentrations are higher than selected limit/target values, EEA member countries, 1997–2006. (Source: EEA, 2010.)

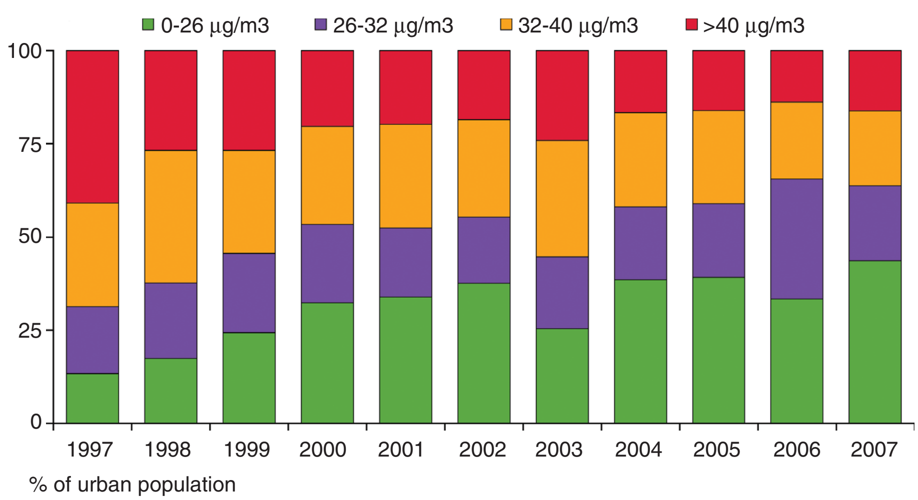

Figure 12.16 Percentage of population resident in urban areas potentially exposed to NO_2 concentration levels exceeding the annual limit value in EEA member countries for the period 1997–2006. (Source: EEA, 2010.)

12.3.6 Urban green areas and urban soils

Urban open space and green areas

In European cities the area occupied by open space, consisting of parks and recreation areas, is on average 30%. Organic matter production does not play a significant role in the operating mechanisms within a city. However, while the green belts play purely recreational and aesthetic roles, they are very important also because they even out the air temperature fluctuations within a city, reduce noise and other pollution, and serve as a habitat for small animals and birds. It is not cost-free, however, to support their functioning, and the labour and fuel spent on irrigation, lawn management, tree planting and care, etc., increases the energy and monetary expenses of a city.

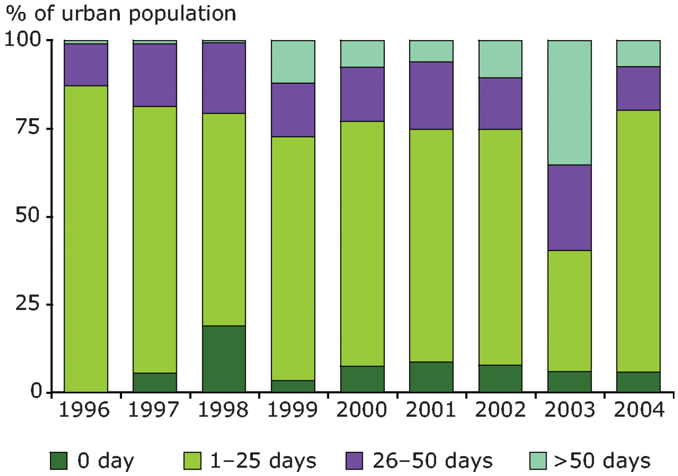

Figure 12.17 Exposure of urban population in EEA member countries to maximum ozone concentration above the 8 h-daily mean target value of 120 µg/m³. (Source: EEA, 2010.)

Trees can nevertheless play an important role in N_r related issues in cities, such as by helping to reduce the effects of particulate matter (PM) and NO_x pollution. The amounts of gaseous pollutants and particulates and the interception of aerosols are greater in woodlands than in shorter vegetation (Fowler *et al.*, 1998), since they have broader leafs and create turbulent mixing of air. Therefore, urban woodlands and the presence of trees in the urban environment can improve air quality quite significantly. McPherson (1998) estimated that in Chicago trees removed 234 tonnes of PM_{10} in 1991 and improved average hourly air quality by 0.4% (2.1% in the heavily wooded areas), while Nowak *et al.* (1997) calculated that trees in Philadelphia improved air quality by 72% by removal of PM_{10}.

Urban soils

Urban soils, which play an important role as sources, sinks and transformers in the nitrogen cycle, represent an area of great concern as regards food supply and supply of sustainable drinking water, and are important in terms of aesthetics and recreation. Soils are designated as urban soils if they are located in watersheds that provide drinking water, food, waste utilisation, and natural resources to cities. Urban soils include also all soils located within cities in park areas, recreation areas, community gardens, green belts, lawns, septic absorption fields, sediment basins or other open or sealed soils inside the city.

The N status and dynamic of urban soils is determined by external factors like N deposition, temperature, rainfall, groundwater N content and groundwater level and internal factors like the geogenic parent material, technogenic substrates, water and air holding capacity, dry bulk density, microbial activity, etc. Technogenic substrates (rubble, construction material, sewage sludge, refuse, and dust) play a key role in the genesis of urban soils. Furthermore they are relatively comparable among cities. Examining the N status of the most important technogenic substrates makes it possible to assess the potential behaviours of urban soils.

12.4 Conclusions, uncertainties and the future development of European cities

The present day situation in our case study, the PAM, reflects to a large extent the metropolisation processes in the area. The urban population is continuing to increase due to urban sprawl, while the density does not increase greatly, which is typical for the Western European region. The further development of the nitrification–denitrification process in wastewater treatment plants has reduced surface water pollution from cities over the last century. However, such wastewater treatment plants operate by denitrifying N_r back to N_2 which can be considered as a substantial waste of an expensive resource. For Paris alone, this loss equates to a potential fertiliser value of around € 30 million per year. Urban sprawl is responsible for an increase of car use in the urban context (public transport is still not adapted to low density areas) and there is an increase of trip length. The globalisation of trade leads to an increase in transport-related N emissions. However, both the trend towards moving industries from Europe to other parts of the world and the strict regulation of industrial pollutants lead to a decrease in industrial N emissions.

The renaissance of the city is a hot topic in Europe. Generally the term addresses the renaissance of the inner city and is applied to the city centre only. However, while suburbanisation is increasing, more and more European cities are expected to turn into urban regions. A partial renaissance of the inner city would probably take place, as well as partial growth of suburbia. Both will be accompanied by either partial decay of suburbia or partial decay of the inner city. There are already vast and increasing differences among cities. Since the breakdown of communism, the development is very different in different regions, but most European cities are currently exposed to drastic economic and social changes. They face tremendous new challenges such as globalisation, ageing societies, shrinking population figures, shrinking household sizes, increasing social divisions, decreasing resources of public authorities, etc. This change from a relatively stable industrial society towards a post-industrial society will shape the development of cities in Europe over the coming decades. The rejuvenation of an attractive city centre can offer the best service locations, plus it can tie a highly mobile urban middle class to a city in the long run. Creation of an efficient public transportation network connecting the suburbs with the city core is an essential aspect. The growth of European suburbia is a dynamic process, yet in most European cities, urban planning efforts concentrate on the city centre, such as in London and Berlin.

If we aim to create a 'neutral' N_r state for cities in Europe, we have to increase recycling of food and water, minimise household waste either through reusing sewage waters or technologically improving treatment plants, and reduce N_r emissions to the atmosphere limiting travel by car as much as possible. The importance of these sources is clearly illustrated by the nitrogen budget of Paris (Figure 12.6). In particular, reducing road traffic NO_x emissions has the largest single potential to decrease N_r emissions from a city such as Paris, while the use of new re-use based sewage systems, have the potential to avoid the waste of N_r inherent in denitrification-based water treatment systems. Such measures could eventually turn urban areas from being a source of nitrogen to becoming nitrogen neutral. These adaptation measures have to be carefully planned and individually tailored.

The following uncertainties regarding nitrogen cycling in an urban system need a better understanding: the mechanisms of dry-deposition processes in urban systems with patchy vegetation; high NO_x emissions and the complex patterns of air flow in densely built-up areas. The N dynamics of urban soil are very uncertain, and while soil represents a major sink of N in natural ecosystems, what happens in urban soils due to, for example, impervious surfaces (roads, etc.) has been little studied. Factors that control denitrification in urban landscapes are related to the presence of green areas within city, but those areas differ from natural landscapes. They have lower densities of biomass and altered decomposition rates.

Interactions between increasing temperatures, especially in built-up areas, and photochemical smog (NO_2 and ground level ozone) are complex and difficult to quantify. Yet, it can be expected that increasing global ambient temperatures may contribute to more frequent occurrences of N_r-related adverse health effects in cities.

There is still some uncertainty regarding the fate of N_r in the septic tanks in low-density suburban residential areas. For example, many of these are fairly old and may not function properly, causing leaking to the groundwater. Also storm events often cause septic tanks to overflow, in which case the untreated sewage is transported directly to the surface waters.

The most immediate task to bring a city to a neutral state in relation to the nitrogen cycle, is to control transport emissions in cities. There are already some examples of sustainable transport policies in cities, showing that public transport can be attractively organised for a densely built-up city, as well as for a large metropolitan area. In the city of Basel, the traffic policy aims to calm traffic and to promote the use of the bicycle. In the 1980s and the early 1990s the Basel traffic policy implemented a variety of environmentally compatible measures in different areas of transport. This multi-level policy could serve as a model for urban development in other cities. Local measures include implementation of a traffic policy with an effective combination of green transport modes; the successful testing of traffic calming measures in residential districts; the safeguarding of high standards for bicycle use; the diversification of modernised bus, tram, and rail systems; the introduction of a customer-friendly pricing policy in public transport systems; the passing of legal regulations in favour of green modes of transport.

Restructuring the labour market (which is the second most important driver of urbanisation after population growth) plays an important role in creating of sustainable transportation network. The city of Copenhagen, which in 1993 introduced a Municipal Plan aiming to design a compact urban structure based on public transport, provides a good example. This required a long-term restructuring of working places according to public transport stations, enhancing and transforming the growth of the city in the harbour area, strengthening the 'green' aspects of the city and restoring and maintaining the historical quality of specific city districts and their diversity.

An increasing interest in deploying the tram-trains concept is growing across Europe in order to fight congestion whilst also cutting carbon and nitrogen emissions. This approach, using proven technologies, combines heavy rail routes with tramways to allow passengers to access key destinations in city centres from the suburbs without making a change, with the aim of attracting people who previously used cars. Germany pioneered the utilisation of combining heavy rail and street running fixed link systems but in the last few years there has also been an upsurge of interest in France and a trial is under way in the UK (connecting Sheffield, Huddersfield and Rotherham in Yorkshire).

Generally speaking, the most effective N management strategies are those that are specifically tailored to individual cities and the ecosystems surrounding them. To develop such schemes will require the construction of detailed, ecosystem-level N_r balances, to help with a deeper understanding of the interplay of inputs, geographical and climatic factors, non-specific management practices, and deliberate N_r management practices that control the fate of N_r in urban landscapes.

Nitrogen budgets can be used as a tool to provide a context for the evaluation of the extent to which human intervention in the N cycle has changed N_r distribution from local to global scales. To gain first insight into the spatial heterogeneity of N_r creation and distribution in urban landscapes, we examined an urban N budget. This is important as it illustrates the differences in N_r creation and distribution as a function of the level of urban development and geographic location.

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