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Title

Nutrient and energy flows related to wastewater management in the Greater Paris: the potential of urine source separation under global change constraints

Abstract

Megacities are facing a twofold challenge regarding resources: ensure their availability for a growing urban population and limit the impact of resource release in the environment. Wastewater management is one of the key urban components intimately linked with resource flows in the city and global change requires that megacities investigate the adequacy of their wastewater management to address the resource challenge.

Taking the greater Paris as a case study, we focus on two main resources and their fluxes related to wastewater: major nutrients, namely carbon, nitrogen and phosphorus, and energy. Future abundance of energy and nutrients at comparable levels to present standards is not guaranteed. Nutrients availability will partly depend on energy availability and phosphorus is also critical by itself. On the other hand, even though Paris has undergone remarkable progress in the last decades regarding the limitation of the environmental impact of its wastewater management, there are still major issues to be addressed: limitation of greenhouse gas emissions, be it from the combustion of hydrocarbons linked with construction, transportation or electricity consumption or the emission of nitrous oxide in the denitrification process; limitation of nutrients release in the rivers. Climate change could have a huge impact on the river Seine's flow: by 2050, it is expected to be 30% lower than today while Paris population is expected to increase by more than 10%, lowering dramatically the possibilities of nutrients dilution.

Is it possible to increase purification yields and simultaneously reduce energy consumption and greenhouse gas emissions and improve phosphorus recycling rate? Confronted to a similar dilemma, many European countries have started implementing source separation techniques in domestic wastewater management, considering that pollution due to wastewater is a misplaced resource that could be better valued.

In fact, the analysis of nutrients flows in the wastewater management of the greater Paris shows very poor efficiency of carbon, nitrogen and phosphorus management regarded as a resource. Energy harvested from organic matter is relatively low compared to theoretical possibilities, nitrogen requires high energy for synthesis of ammonium in fertiliser plants and high energy for denitrification in wastewater plants, with a third of the flow still discharged to the river and phosphorus is only partially recycled in agriculture and not recovered from sludge ashes.

Considering that nitrogen is the limiting factor of Parisian wastewater treatment plants capacity and that ¾ of nitrogen in wastewater comes from urine, the SIAAP, Syndicat Interdépartemental d'Assainissement de l'Agglomération Parisienne, a public institution in charge of wastewater end transport and treatment for three quarters of the population of the greater Paris, has conducted a study to assess the potential of urine collection for the future housing developments of the greater Paris.

The study concludes that urine diverting toilets, coupled with urine storage tanks at the bottom of each new building, collection by trucks and specific treatment, would have a better carbon footprint than the extension of the current wastewater treatment plants. Phosphorus and nitrogen release in the environment would be much lower, phosphorus recovery would be much more efficient and, depending on the technology chosen, nitrogen recovery could even be feasible. Low-tech treatment systems would require less energy but high-tech systems could require larger energy inputs.

The transition towards a paradigm of source separation in Paris still faces numerous challenges: citizens' involvement in urine diversion, economic viability of the model, lack of experience of the different stakeholders involved in new housings construction and maintenance, inexistence of source separation in French regulation, effectiveness of nutrients recycling in agriculture, etc. As it has been done in many cities of Northern and Central Europe, the implementation of a pilot project will be a crucial step for a better assessment of this potential.

Considering the current development of sewer-free or decentralised toilet waste management, both in high-standard new housing developments and in the poorest districts of megacities, source separation appears to be a promising alternative to conventional sewerage systems. Megacities with low sewage network coverage can benefit from worldwide source separation experiences to optimise their nutrient and energy challenge in wastewater management whereas already equipped megacities can consider its implementation for extension or urban renewal projects.

Article

1. Introduction

Since 2007 and for the first time in the history of humankind, the majority of the world population lives in cities (United Nations, 2014). And in 2014, the United Nations list 28 megacities of more than 10 million inhabitants around the world, accounting for about 12% of the world urban population. These megacities epitomise the environmental challenge of urban dwelling regarding resources: tremendous amounts of resources need to be imported for the city to function and the concentration of more than 10 million inhabitants in a relatively small area potentially leads to formidable ecological impact, pre-eminently on the local environment but also noteworthily at a global level. In a context of global change, two issues thus need to be addressed by megacities: 1) ensure the availability of these resources; 2) limit to an acceptable level the ecological impact of the circulation of these resources, both on the territory of the megacity but also, within an rationale of responsible ecological footprint, in the territories upon which the megacity relies to function.

For this purpose, the study of urban metabolism through substance flow analysis can help understand the stakes of resource flows, evaluate the sustainability of the current paradigm and investigate possible evolutions of this metabolism. At a global scale, the most critical flows regarding their environmental impact are considered by Steffen et al., 2015 to be the biogeochemical flows of nitrogen and phosphorus. Their study puts forward nine main control variables of the Earth system and suggests planetary boundaries under which these control variables should stay to prevent major shifts in the regulation of the Earth system stability. Along with biosphere integrity, nitrogen and phosphorus flows are considered to be in the highest risk zone, ahead of the climate change control variable. While the terrestrial carbon cycle is being modified in the order of magnitude of 10% by fossil fuels burning and entails the current climate change, the terrestrial nitrogen cycle is increased by more than 100% due to human activities (Gruber and Galloway, 2008). The concern about disruption of the nitrogen and phosphorus cycles has been broadly studied and documented. It is of particular significance in Europe where the nitrogen cycle intensity is about 4 times greater than the biospherical one leading to numerous negative consequences, from aquatic and terrestrial eutrophication to poor air quality and climate change (Sutton et al., 2011).

Currently, reactive nitrogen availability is mainly linked with energy availability. Most reactive nitrogen is produced in the form of chemical fertilisers and its synthesis requires about 43 MJ/kgN (Larsen et al., 2013, §2), mostly provided today by fossil methane. The abundance of inert nitrogen in the atmosphere does not bring any concern about elemental nitrogen availability but the energy cost of reactive nitrogen synthesis makes nitrogen availability sensitive. On the other hand, extracting phosphorus from mines also requires high amounts of energy for the production of fertilisers (around 29 MJ/kgP, ibidem) but the availability of phosphorus in itself is much less obvious since concentrated phosphorus ores represent a fossil resource, unevenly spread at the surface of the globe. Phosphate rock has recently been added on the list of critical raw materials by the European Commission (European Commission, 2014), emphasising the criticality of phosphorus availability for Europe.

In megacities, nitrogen and phosphorus flows are predominantly linked with human metabolism. Our body requires the consumption of around 2.7 kgN/year (WHO et al., 2007) and 200 gP/year (Brownlie, 2015). As a consequence, two major components of urban metabolism are at stake in nitrogen and phosphorus flows: 1) food supply, since nitrogen and phosphorus are provided by our diet and 2) waste and wastewater management, since food waste and human excreta in the form of urine and feces are the main residues of our nitrogen and phosphorus consumption. Analysis of nutrients flows in the city thus requires addressing the more global water-energy-food nexus as we can see that all these features are tightly intertwined (United Nations, 2015). Taking Paris as a case study, we will scrutinise the sustainability of nitrogen and phosphorus flows in megacity metabolism, their link with carbon and energy flows, and try to find paths of optimisation in order to ensure nutrients availability and acceptable levels of environmental release.

2. The peculiarity of Paris

Paris is the biggest megacity of the European Union, just ahead of London. The population of the urban area of Paris is about 12.5 million inhabitants (INSEE, 2015a, §1.4), with one of the densest city centres in the world of more than 21,000 inhab/km² (INSEE, 2015b). The impact of Paris on its environment is amplified by the fact that it is drained by a relatively small river: the monthly minimum flow with a 5-year return period of the river Seine in Paris is 94 m^3/s (DRIEE-IF, 2014), leaving only a dilution capacity of 650 L/pers/day. This means for example that the release of minimum metabolic nitrogen requirements in the river Seine would theoretically exceed about 30 times the 0.5 $mgNH_4^+/L$ river quality limit imposed by the transcription in French regulation of the European Water Framework Directive (WFD).

Given that Paris drains urine and feces in its sewers to wastewater treatment plants, this low dilution capacity of the Seine river requires flawless management of the whole wastewater system, achieving more than 95% global collection and treatment efficiency – not to mention impacts on smaller urban rivers. And even if this efficiency was actually reached, a megacity like Paris would still release the equivalent of more than 600.000 untreated inhabitants in its receiving environment. The impact of Paris on the Seine reached unprecedented levels in the 70s with nearly no oxygen in the river and more than 5 $mgNH_4^+/L$ concentrations downstream. Since then, considerable efforts displayed in wastewater management lead to being close to WFD physicochemical quality thresholds. However the marginal cost of quality increase is now becoming critical and considerable investments are necessary to further improve conventional wastewater treatment efficiency.

In terms of food supply, Paris is surrounded by rich agricultural land but its food source has gradually shifted from a local supply in the XVIIIth century to an international supply system: according to Billen et al., 2012, one quarter of the arable land that provides the nitrogen food content to Parisian dwellers is located in South America, since its soybean production feeds the French livestock that is eventually imported in Paris. On the other hand, the agriculture of the Seine river basin is now dedicated to export 80% of its highly specialised cereal production. The nitrogen and phosphorus environmental release of the Parisian basin agriculture leads to non-compliance of France towards its international commitments. For example, the 1992 Oslo-Paris convention urged the Seine river basin to divide by 2 its nitrogen fluxes to the sea between 1985 and 1995. Instead, these fluxes have steadily risen by 2.5% per year between 1985 and 2000 (Agence de l'Eau Seine Normandie, 2009).

3. Carbon, nitrogen and phosphorus (C, N & P) flows linked to human metabolism in Paris

3.1 The metabolism of Parisians

Focusing on human metabolism, we seek to determine the induced phosphorus, nitrogen and carbon flows. The chosen perimeter for human metabolism analysis is the territory of wastewater collection of the SIAAP (Syndicat Interdépartemental d'Assainissement de l'Agglomération Parisienne), a public institution in charge of wastewater end transport and treatment for about three quarters of the population of the greater Paris. For the sake of simplicity, these people will be further referred to as Paris-SIAAPians and this perimeter will be called Paris-SIAAP. The calculations are made for the year 2013.

The nutrient flows induced by the metabolism of this population include the wastewater management system, the solid waste management system, the agricultural land and agricultural and agro-industrial food production processes. Various data have been compiled and cross-checked in order to present the best available representation of these flows. The results are summarised in the 3 schemes displayed below in §3.4.

Data of population census, tourism and business trips have been gathered from studies of French ministries. They have been used to get the yearly average instantaneous number of people living – ie eating and excreting – in Paris-SIAAP:

- Children under 2.5 years old, accounting for an estimated less than 1% of total human metabolism, have been excluded;
- dwellers temporarily out of Paris-SIAAP for holidays or work have been deduced *pro rata temporis*;
- non dwellers coming to Paris-SIAAP for tourism or work avec been added *pro rata temporis*.

The actual yearly average instantaneous population is thus estimated to be of around 8.4 million people over

2.5 year old in 2013 as compared to a total legal population of 9 million people.

Children and adult food intake has been estimated from the 2nd national survey on food consumption (AFSSA, 2009) with a 0.16 mass ratio of nitrogen per protein (WHO et al., 2007) and a 27 g/MJ ratio of carbon per food energy content derived from Svardal and Kroiss, 2011. Carbon consumption in food provides energy to the body through respiration. Based on energy content of urine and feces from Larsen et al., 2013, §17, energy intake ratio is thus estimated at 90%, leading to 280 kgCO_2 breathed on average during the year. This figure is possibly underestimated considering up to 20% higher literature values eg Barles, 2013 or Villarroel Walker et al., 2014. In general, carbon flow values are much more uncertain than nitrogen or phosphorus ones due to low data availability of direct measurement of carbon content. Depending on the organic matter considered, carbon to energy or carbon to Chemical Oxygen Demand (COD) ratios vary greatly which leads to higher uncertainties.

Unlike carbon, N & P are mostly excreted by the human body through urine and feces. Between 1 and 2% of our total life intake is stocked before adult age to build our body. An estimated 1% of N & P is excreted otherwise through sweat, hair, menstruation, etc. but part of these excretions end up in the wastewater network together with blackwater thus leading to acceptable approximation of food intake N & P being transferred to wastewater systems. Literature data of N & P content of urine and feces vary on a quite important range but remain coherent with our calculated data (4.8 kg/pers/y for N and 0.45 kg/pers/y for P).

3.2 Downstream fate of Parisians' metabolism

Actualised from Lesavre, 1995, 97% of the Paris-SIAAP population is estimated to be connected to the SIAAP wastewater network. Data analysis from the sanitation master plan of the SIAAP area, currently under revision (SIAAP, 2012), leads to an estimated 3% of C, N & P of wastewater being discharged with rain overflows and only 0.3% being discharged permanently during dry weather, accounting for around 25,000 people-equivalent. These data are possibly underestimated regarding the difficulty to quantify losses from the wastewater network, not to mention sewage leaking in the ground. Nevertheless, these figures have been taken as such in the flow analysis.

Operational data of the 5 wastewater treatment plants of the SIAAP have been investigated to determine C, N & P fate in the wastewater management process. Non-metabolic contributions to C, N & P inflow in treatment plants have been calculated by difference with other values and compared to available data on industrial water, greywater and rainwater. Purely industrial flows appear to be quite low on Paris-SIAAP territory. In Paris-SIAAP, non-metabolic phosphorus is steadily decreasing of around 25 g/pers/year with bans on phosphates in detergents. P content of greywater makes comparison with old data or data from other countries quite difficult since data vary on an extremely wide range. Recent available data on Paris seem compatible with our calculated data (Deshayes, 2015, unpublished data). Non-metabolic N release in the wastewater system also seems to be in a good order of magnitude.

P discharge in the rivers represents 18% of total P entering the networks. But only half of the sludge of the SIAAP is directly spread on agricultural land or composted, the other half being incinerated in various facilities. Although technically possible today and becoming mandatory in different European regions (ESPP, 2015), phosphorus recycling from ashes is not done in Paris, leading to a rate of fossil phosphorus recycling from the wastewater management system of only about 40%.

N is mostly emitted from wastewater treatment plants in the form of gas, predominantly N_2, but also in small proportions in the form of NH_3 and N_2O. The latter being a powerful greenhouse gas, more accurate estimations of N_2O release are currently being conducted. An estimation made before the completion of nitrogen treatment showed that it could raise the total carbon balance of the SIAAP by more than 50% in terms of CO_2 equivalent emissions (Tallec et al., 2007). N recycling to agriculture is negligible. N discharge in the river from the wastewater treatment plants respects the European regulatory threshold of 30% but the real global rate of N river discharge from the wastewater system is about 38%. In other words, it is as if more than 4 million people discharged daily their urinary nitrogen in the river Seine, mostly in the oxidised NO_3^- form. Nevertheless it must be highlighted that regarding the ecological impact on the Seine river ecosystem before the estuary, the ammonia concentration are not so far from the WFD good status. On the other hand, nitrite concentration levels are still high and remain of great concern regarding WFD good status.

C content of wastewater is increased during the treatment process with the addition of methanol, accounting for 5% of total C inflow. It is worth mentioning that methanol is currently processed from fossil methane, making wastewater treatment plants net emitters of fossil carbon through methanol degradation. In Paris-SIAAP, it accounts for an additional 30% of total carbon emissions of wastewater treatment. In the plants, 10% of C is converted to methane via anaerobic digestion. However, methane carbon is in a highly reduced state so the rate of energy conversion to methane is much higher and reaches around 25% of total chemical energy inflow. The overall rate of wastewater C recycling to agriculture is about 15%.

3.3 Upstream origins of Parisians' metabolism

Understanding the origins of metabolic C, N & P requires investigating the whole food production system. Our study is mostly based on the works of the PIREN-Seine research program which has explored in details the past evolution and the current state of food production for the Greater Paris – see eg the nitrogen flows presented in Billen et al., 2011. Three food production systems are at stake to feed Paris: 1) soybean production in South America for ¼ of the surfaces; 2) intensive meat production territories in Western and Northern France for ⅔ of the surfaces; 3) intensive cereal production around Paris for the remaining lands. These 3 agricultural territories, the internal recycled flows – eg through manure spreading – and the agroindustrial transformations of food produced have been summarised in one process in the schemes below.

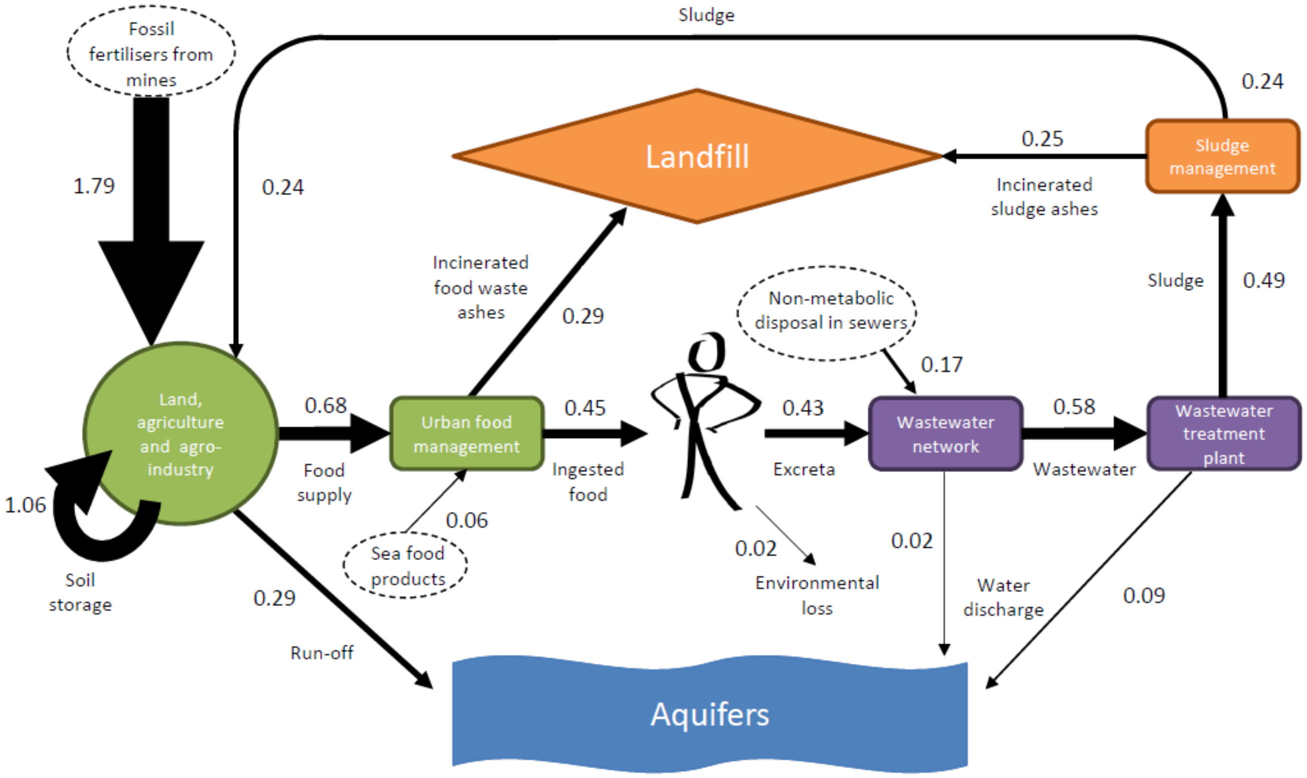
Given the importance of South American soybean importation as feed for French livestock and the fact that about ⅔ of the protein ingested by Parisians come from animals, it appears that nearly half of the nitrogen of the Parisian diet comes from biological fixation. The other half is produced in fertiliser plants thanks to the Haber-Bosch process. Nitrogen losses to the aquifers account for about 15 kg/pers/year, 7 times more N losses than from the sewage system. ¼ of total N environmental losses is considered to be released in gaseous forms of mainly N_2, NH_3 and N_2O. The difference between food importation in the Greater Paris, based on data from the Ministry of Agriculture in Billen et al., 2011, and the food intake of Parisian (AFSSA, 2009) leads to a 40% total food waste. With practically no biowaste recycling in Paris, this food waste is currently burnt in incineration plants and N mainly returns to the atmosphere after reduction of NO_x to N_2 in the treatment of gases.

The phosphorus agricultural cycle is much different since about half of the phosphorus that is spread on lands ends up sequestrated in the soil. Based on analysis of food provision of Paris given by Billen et al., 2011, P cycles have been adapted from France global P cycles (Senthilkumar et al., 2012). The agriculture feeding Paris has been considered comparable to the mean French agriculture, which leads to higher uncertainties on results. In all the schemes below, sewage sludge is represented as going to the food production process of Paris whereas a large part of the food production of these fields, located 200 km around Paris, is dedicated to exportation. However, Senthilkumar et al., 2012 give a comparable fossil to recycled fertiliser proportion in French agriculture. P losses to aquifers from the agricultural sector represent ¾ of total P losses to aquifers but remain proportionally much lower than N losses to aquifers. The P from biowaste, estimated to 40% of P in total food supply as for N, ends up in landfills after incineration.

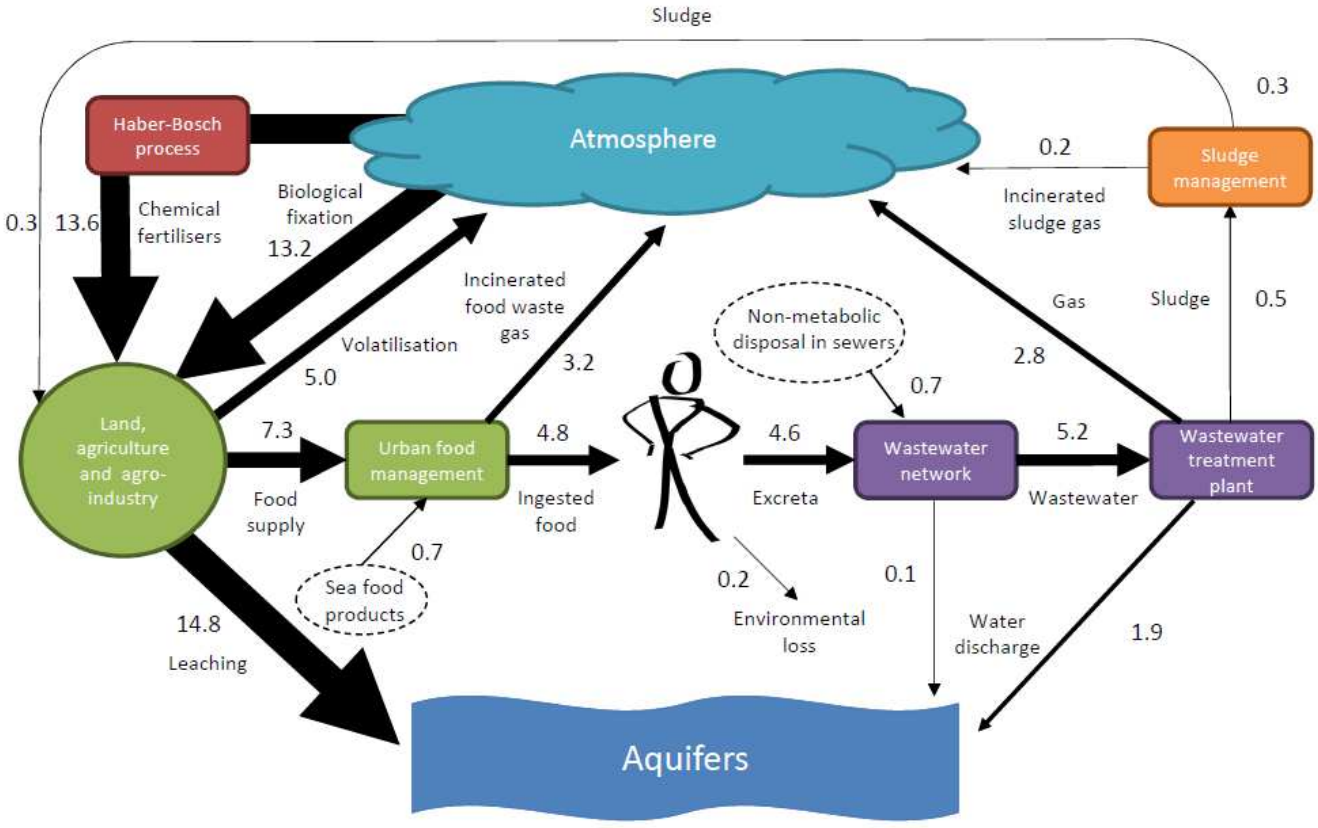
Carbon in food comes from photosynthesis on the fields. A 150% rate of photosynthetic fixation was assumed to account for carbon staying in or returning to the soil. Based on mean French data from IFEN, 2007, a net carbon de-stocking from agricultural soils of 33 kg/pers/year is assumed. Two thirds are due to change in practice such as grassland conversion into intensive culture, one third is due to soil erosion, calculated from Cerdan et al., 2010 with an assumed 1.5% rate of carbon in eroded soils. These values present high uncertainties and spatial variabilities but are compatible with calculated values of phosphorus loss. They show a current carbon impoverishment of French agricultural soils.

3.4 Global schemes

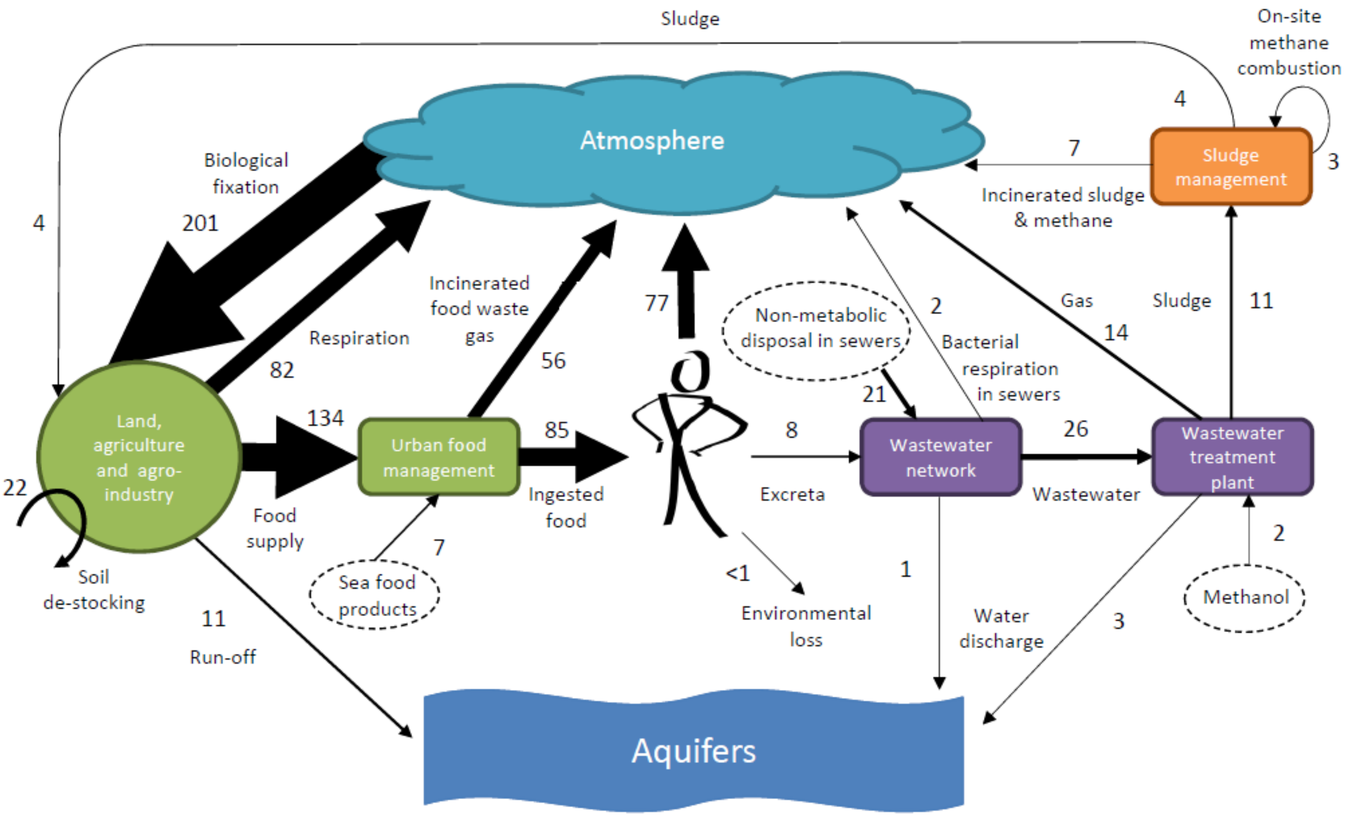
3.4.1 Phosphorus flows related to Parisians' metabolism in 2013 (kg/pers/year)



3.4.2 Nitrogen flows related to Parisians' metabolism in 2013 (kg/pers/year)



3.4.3 Carbon flows related to Parisians' metabolism in 2013 (kg/pers/year)



3.4.4 Comments en schemes

The current socio-ecological regime of Paris for N & P (Fischer-Kowalski and Haberl, 2007), with a combination of high-level chemical fertiliser use, food waste incineration and low-rate recycling in wastewater treatment appears rather linear and most likely not sustainable. On one hand, the overall recycling rates of N & P in the city are respectively estimated around 3% and 30%. On the other hand, 3 to 4 times more artificial fertilisers are used by the food production system as compared to corresponding N & P ingestion by Parisians.

A brief analysis of upstream and downstream energy inputs shows that fertiliser production to feed a Parisian accounts for about 700 MJ/pers/year (see §1) and low-recycling wastewater treatment requests about 470 MJ/pers/year (SIAAP data). It represents a little more than 1% of total French final energy consumption per person.

The food production system appears as the most intense process in terms of absolute values of flows and strong modifications could be achieved (see eg Billen et al., 2011, Solagro, 2014 or van Grinsven et al., 2015). But even without changing this process, an evolution in food management in the city could have tremendous upstream effects. For example, lowering the food waste rate from 40% to 20% and lowering N & P intake from 200% to 150% of body requirements (see §1) would lower N release in aquifers by 5 kg/pers/year, about 2.5 times the current total release of nitrogen from the city itself. Lowering the proportion of animal products in food is also a strong lever, as illustrated by the demitarian diet put forward in the Barsac declaration (NinE, 2009).

Finally, the wastewater management itself could follow different evolutionary paths. Based on nutrient flow analysis in the megacity of London, which faces similar challenges, Villarroel Walker et al., 2014 have studied 4 ways of changing nutrient metabolism of London, among which urine separation is the best option for nutrient recycling. This concept has increasingly been studied since the 1990s and appears for many as a promising opportunity towards more sustainable cities (Wilsenach et al., 2003).

4. The opportunity and challenge of urine source separation in the Greater Paris

Strong incentives have driven the SIAAP to study urine separation implementation for the Greater Paris. The most limiting factor of the wastewater treatment system is nitrogen. The size of the wastewater treatment plants and the energy and reactants consumption of the SIAAP are mostly imposed by nitrogen treatment. Furthermore, Paris is confronted to a major scissor effect: climate change should lower the Seine minimum flow of around 30% by 2050 (Habets et al., 2011) while political decisions of developing the Greater Paris are expected to maintain or raise the current 0.5% of population growth and increase Paris population of at least 10% in the next 20 years. Reaching and maintaining the above mentioned 0.5 $mgNH_4^+/L$ quality in the river Seine will thus require the construction of new treatment capacities at better levels. Considering that around 85% of metabolic nitrogen is excreted through urine (Larsen et al., 2013, §17), urine separation in Paris has the potential of exiting ¾ of total nitrogen inflow in the wastewater treatment plants.

A study conducted by the SIAAP on this topic in 2013 (Caby, 2013) concludes that the wastewater treatment plants of the SIAAP will be at 106% treatment capacity on nitrogen in 2030 and that collecting the urine from one million inhabitants of the Greater Paris before this year would avoid having to build new treatment capacities. For example, implementing urine diversion in new housing developments would be sufficient to meet this goal. At the same time, collected urine could be directly applied to land after storage, such as in different locations in Sweden (see eg Caby, 2013 or Larsen et al., 2013, §28) or concentrated such as in the different VUNA pilot projects in Switzerland and South Africa (Etter et al., 2015). Urine collection could completely change the paradigm of human metabolism management in the Greater Paris and increase nutrient recycling.

The Caby, 2013 study has built a scenario with urine collection from dry urinals and urine diverting toilets, local storage of urine in tanks and collection by trucks, leading to 150 trucks per day in the whole SIAAP perimeter and up to 10 times lower carbon emissions than with conventional treatment. The low-carbon nuclear electricity in France makes VUNA treatment very competitive, with 1.2 $kgCO_2/kgN$ emissions to produce fertiliser from urine, compared to 5 $kgCO_2/kgN$ for standard chemical nitrogen fertilizer with Haber-Bosch process (data from ADEME, 2015 and Larsen, 2015).

Urine separation in the Greater Paris still faces numerous challenges: urine collection is nearly not implemented anywhere in France (and probably not anywhere else in the world at such large scale!) and would face the lack of experience of the different stakeholders; urine collection and agricultural valorisation are inexistent in French legislation; citizens' involvement will be necessary; the yield of urine collection is hard to anticipate; economic incentives on reducing carbon emissions are currently much too low to make urinary nitrogen competitive, etc. The implementation of a pilot project will be a crucial step for a better assessment of the potential of urine source separation in Paris both on social aspects and on technical ones.

Even if urine collection was largely implemented in Paris in the beginning of the XIXth century (Caby, 2013), reconnecting Paris with its heritage of urine separation will be challenging. Two centuries later, re-introducing this “innovation” in the well-established paradigm of flush toilets and centralised wastewater management will most likely face society's aversion to change. “Only wet babies like change” (Weiss, 2009).

5. Conclusion

The ecological footprint of Parisians' metabolism appears rather unsustainable and highly impacting, both on the local environment and on the territories Paris relies upon. If the idea of limiting carbon introduction in the atmosphere is paving its way at the international level, recycling fossil phosphorus and limiting nitrogen introduction in biosphere appear to be a crucial stake for megacities like Paris. Alfred Lotka pointed out in 1924 that the Haber-Bosch reaction, with the large food production it enables, marked “the beginning of a new ethnological era in the history of humankind” (quoted by Billen et al., 2011). The limits of this new era prompt us to reinvent urban metabolism, and wastewater management will play a crucial role in it. It took about 100 years to build the current wastewater system of Paris: urine separation seems a challenging but promising concept for the future evolutions of wastewater management in megacities.

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