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Keywords

Biogeochemical imprint; water-agro-food system; urban metabolism; megacity; nitrogen cycle; phosphorus cycle.

Abstract

Megacities are facing a twofold challenge regarding resources: (i) ensure their availability for a growing urban population and (ii) limit the impact of resource losses to the environment. This paper focuses on two essential resources – nitrogen and phosphorus – and challenges their sustainable management in the water-agro-food system of Paris Megacity. An in-depth analysis of the nitrogen and phosphorus imprint of Paris Megacity was conducted, originally centered on human metabolism through consumption and excretion of these two elements. Upstream, the whole agricultural production that feeds Paris Megacity was scrutinized and nitrogen and phosphorus flows in the agro-system were fully documented. Downstream, the analysis of solid waste and wastewater management in Paris Megacity showed the fate of nitrogen and phosphorus imported into the city. Paris Megacity appears to rely on a very complex and international agro-food system, requiring high levels of chemical fertilizers and strongly impacting the environment through nutrient environmental losses. On the other hand, solid waste and wastewater management appears to be mostly disconnected from the agro-food system: even if the release of nitrogen and phosphorus into the environment has largely decreased in recent years, their recycling rate remains very low. This overview of the water-agro-food system of Paris Megacity suggests that an optimal management of nitrogen and phosphorus in the three subsystems (agriculture, waste management and sanitation) should be integrated within a comprehensive approach linking agriculture and urban residues. This analysis thus constitutes a groundwork on which paradigm shift scenarios of the global water-agro-food system could be constructed.

Graphical Abstract

Highlights

- Paris Megacity externalizes most of the N&P imprint of its water-agro-food system.
- Animal food production requires 10 to 30 times more resources than vegetal food.
- Wastewater N imprint per capita is 4 times higher than for vegetal food production.
- Urban residue management in Paris Megacity is poorly connected to agriculture.
- Imprint minimization requires integrated nutrient policy at local & global scales.

1. Introduction

Born of a process of sociospatial specialization, cities are characterized by the externalization of most of their metabolism – the flows of material and energy necessary to sustain urban life and urban functioning – and by their dependence upon various areas and ecosystems located outside their boundaries, for both the supply of resources and the disposal of waste. The industrial era has increased this dependence and remoteness to the point that the urban environmental impact is greater in these supply and emission areas than in the city itself (Barles, 2015). Today the imprint of urban environments can be found throughout the world (Billen et al., 2012a) and for every environmental compartment, water being one of the most impacted. Cities' dependence upon remote areas also questions their sustainability and their ability to face socioecological crises that could impact their metabolism as a whole: climate change and extreme climate events, change in geopolitical conditions, economic crises, etc.

More than other cities, megacities are characterized by their huge need for material and energy (Kennedy et al., 2015), among which food and water are of utmost importance for the life of their inhabitants. Megacities are not just bigger than most cities: their large and diverse populations, their spatial extension, the amount and diversity of activities that characterize them, the complexity of their functioning make the organization of megacities' metabolism particularly delicate, especially regarding food and water from the point of view of both supply and discharge through waste and wastewater. These have a strong impact on biogeochemical cycles. The characterization of this impact is a key to understanding megacities' metabolism and to considering change in water and food management. This makes it necessary to (i) identify the main biogeochemical flows in terms of socioecological relevance and to analyze the biogeochemical processes involved, (ii) quantify these flows and (iii) locate them at the different stages of their circulation.

Nitrogen (N) and phosphorus (P) can be considered as the most critical biogeochemical flows regarding their socioecological impact. Steffen et al. (2015) put forward nine main control variables of the Earth system and suggested planetary boundaries under which these control variables should stay to prevent major shifts in the regulation of the Earth system's stability. Along with biosphere integrity, N and P flows are considered to be in the highest risk zone, ahead of the climate change control variable. The concern about disruption of N and P cycles has been broadly studied and documented. It is of particular significance in Europe where the N cycle intensity is about five times greater than the biospheric cycle, leading to substantial negative damage, from aquatic and terrestrial eutrophication to poor air quality and climate change (Sutton et al., 2011). The environmental dispersion of P is also a matter of concern regarding fertilizer and therefore food production (Cordell, 2010). Phosphate rock has recently been added to the list of critical raw materials by the European Commission (European Commission, 2014).

Megacities play a major role in N and P flows and depend on them. Urban dwellers' metabolism is embedded in a complex worldwide water-agro-food system resulting in an equally complex biogeochemical imprint. Some studies have provided an overview of urban metabolism through substance flow analysis regarding N or P (Svirejeva-Hopkins et al., 2011; Færge et al., 2001; Forkes, 2007; Barles, 2007) or considered the impact of urban waste and/or wastewater on the environment (Morée et al., 2013). Others have focused on the urban food-print and show the relevance of a spatialized approach (Billen et al., 2009, 2012a, 2012b, 2012c; Chatzimpiros and Barles, 2013). However, it seems important to entertain a broader view and to explore both the downstream and the upstream imprint of urban metabolism, as demonstrated by Schmid-Neset et al. (2008) for P. This approach contributes to characterizing the current socioecological regime (Fischer-Kowalski and Haberl, 2007) of megacities.

In this paper, we therefore focus on Paris Megacity, and the N and P flows involved in its food production, supply, consumption and discharge. To determine the biogeochemical imprint of human metabolism in Paris Megacity, its water-agro-food system has been divided into three subsystems: (i) food production in the agricultural system that feeds Paris Megacity, (ii) food waste management from production at the farm to the actual ingestion of food by humans and (iii) human excreta management in the city itself. In each of these subsystems, a detailed and regionalized analysis of N and P flows was conducted. We aimed at qualitatively and quantitatively comprehending the stakes of the biogeochemical imprint for sustainable development of a megacity such as Paris. For the sake of this study, we therefore characterized the imprint of Paris Megacity by the magnitude of the flows of resources (here N and P) required to sustain its food supply and the flows of wastes discharged into the environment as a consequence of food consumption. We also determined the spatial distribution of these flows.

2. Material and methods

As recommended in the early work by Baccini and Brunner (1991), the borders of our system are defined in this section, as well as the key issues selected.

2.1 Spatial and temporal frame

2.1.1 Spatial frame

The urban agglomeration of Paris is ranked the 25th largest city in the world by the United Nations (United Nations, 2014). It is the largest city of the European Union and, with a population of more than 10 million inhabitants, it is classified as a megacity. The definition of a city remains controversial and the setting of its boundaries can vary greatly depending on the definition adopted. In this paper, we choose to follow the French National Institute of Economic Statistics and Studies' (INSEE, www.insee.fr) definition of the urban unit. The main characteristic of an urban unit is that the distance between two inhabited buildings does not exceed 200 m. In this sense, Paris Megacity is composed of 412 municipalities totaling 10,550,350 inhabitants in the official 2012 census and has a density of 3,700 cap/km² (INSEE). The term "Paris Megacity" will be used in this paper to refer to the Paris urban unit.

Paris Megacity as an urban unit should be distinguished from three other perimeters that are also commonly used to define Paris, illustrated in Table 1 and Figure 1:

(i) the Paris city center. This is the core municipality of Paris Megacity representing 21% of its population. It is one of the densest city centers in the world with more than 21,000 cap/km² (INSEE).

(ii) the Paris urban area. The INSEE definition adds to the Paris urban unit the municipalities where at least 40% of the residents and working population work in the Paris urban unit. Paris Megacity accounts for 85% of the population of the Paris urban area and is five times denser.

(iii) the Ile-de-France region. This is the administrative region in which Paris Megacity is included. Its population is about the same as the Paris urban area, but their respective perimeters differ slightly.

Table 1. Population and density of Paris: city center, urban unit, urban area and Ile-de-France administrative region (data: INSEE, year 2012).

	Units	Paris city center	Paris urban unit	Paris urban area	Ile-de-France region
Population	cap	2 240 621	10 550 350	12 341 418	11 898 502
% of Paris Megacity		21%	100%	117%	113%
Population density	cap/km²	21 258	3 709	719	991

Figure 1.

This study covers the metabolism of people who are actually inside Paris Megacity and the results are expressed in yearly averaged figures. Data from the population census, commuting patterns, tourism and business trips have been gathered from studies conducted by French public institutions (INSEE, authorities in charge of economy and tourism, Institut d'Aménagement et d'Urbanisme de la Région Ile-de-France). They have been used to obtain the yearly average instantaneous number of people actually eating, discarding waste and excreting urine and feces: dwellers temporarily out of the city for holidays or work have been deducted *pro rata temporis*; nondwellers coming to the city for tourism or work have been added *pro rata temporis*.

As stated, the imprint of Paris Megacity largely exceeds its boundaries and each of the three subsystems studied covers a specific imprint zone that can sometimes overlap. Paris Megacity lies within the Seine River basin. It is located 220 km upstream from the estuary where the Seine River flows into the *Baie de Seine* (Seine Bay), as well as into the contiguous North-West Channel and Southern Bight of the North Sea, and is responsible for the development of harmful algal blooms causing severe damage to fish and shellfish populations (Lancelot et al, 2007; Passy et al., 2013, 2016). The Seine River basin has therefore been classified as a sensitive area subject to eutrophication in the sense of the 1991 Urban Waste Water Treatment (UWWT) Directive (European Council Directive 91/271/EEC). The 2015 Seine River basin management plan aims at reaching good ecological potential for 2021, as required by the European Water Framework Directive (WFD) (2000/60/CE), including reduction of N and P concentrations. Moreover, the 1992 Oslo-Paris convention required the Seine River basin to halve its N and P flows to the sea between 1985 and 1995. The target on P has been reached, but the flows of N show an opposite trend of +1% per year over the last 30 years (AESN, 2013).

2.1.2 Temporal frame

In recent years, the most significant changes in the water-agro-food system of Paris Megacity have been the works on wastewater treatment plants in order to comply with the UWWT Directive. This directive requests that the wastewater treatments withdraw 70% of the N and 80% of the P contained in the urban wastewater in sensitive areas subject to eutrophication. This objective was first reached for Paris Megacity's main wastewater treatment system in 2012 (cf. the dedicated Internet site of the French Ministry of Ecology for detailed information on the compliance with this directive on http://assainissement.developpement-durable.gouv.fr). Therefore we chose to describe the imprint of Paris Megacity in 2012. However, because of constraints related to the availability of data, our analysis of the agro-food system is based on figures from 2006. There has been no major shift in the agriculture since this period (Le Noë et al., 2017).

2.2 The agro-food system that feeds Paris Megacity

Evaluating the environmental imprint of Paris Megacity over its food supplying areas requires (i) quantifying Paris Megacity's consumption; (ii) identifying the areas supplying food to Paris Megacity; (iii) evaluating agricultural production and environmental losses from agriculture for each area contributing to the food supply of Paris Megacity and (iv) calculating the environmental imprint of Paris Megacity as the fraction of the environmental losses attributable to food supply of Paris Megacity in each contributing area.

2.2.1 Apparent food consumption (availability)

Data on the availability of food commodities, based on the analysis of national accounts, are provided by INSEE. These data correspond to the apparent food consumption of the French population as a whole, including wasted or discarded parts at the retail and domestic level. We have considered that national data on food consumption can appropriately be applied to Paris Megacity, as confirmed by more detailed inquiries on dietary habits in France (AFSSA, 2009).

Owing to a detailed compilation of the N and P content of each item from the INSEE nomenclature based on information from the CIQUAL and USDA databases on food composition (https://pro.anses.fr/tableciqual/; http://ndb.nal.usda.gov), all data collected have been converted to tons of N per year (tN/y) and tons of P per year (tP/y).

2.2.2 Agricultural trade

The trade exchanges of agricultural products between French departments (NUTS3 in the European Union geocode standard, the administrative district between the municipality and the region) were obtained from the French database SitraM (Système d'Information sur le Transport des Marchandises; http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/). It annually identifies the transport of 50 categories of agricultural products between French departments by roads, railways and navigable waterways, as well as exchanges with foreign countries (customs database). Automated software has been developed by Silvestre et al. (2015) for the analysis of these data. Le Noë et al. (2016) used it to establish a complete matrix of the flows of agricultural commodities exchanged between 33 French agricultural areas (defined by groupings of departments based on the similarity of their agricultural system; see Figure 3) as well as foreign countries grouped into 12 macroregions (Lassaletta et al., 2014). From these data, the relative contribution of each of these 47 agricultural regions to the total Ile-de-France food supply was calculated, separately for vegetal and animal proteins. We assumed that there was no significant typological difference between Paris Megacity's food supply and Ile-de-France's food supply; therefore, the food supply of Paris Megacity was deduced by simple application of population ratios.

2.2.3 Agricultural production and environmental losses of supplying territories

The GRAFS approach (Generalized Representation of Agro-Food Systems), first developed for N flows by Billen et al. (2014), then extended to P and C by Le Noë et al. (2017), describes the agro-food system of a given region by considering four main compartments exchanging N and P flows: arable lands, grasslands, livestock biomass and local population. The GRAFS approach makes it possible to draw direct links between different aspects of the hydro-agro-food system, e.g., the relation between livestock breeding, grassland areas and forage crops and the relation between fertilization of arable lands and grasslands and N environmental losses.

The GRAFS approach is based on a detailed budget of N and P flows including production, transformation and consumption of animal and vegetal products, inputs of N and P fertilizers, atmospheric N and P deposition, symbiotic N_2 fixation, P embedded in feed additives, leaching and erosion in each agricultural region.

The agricultural and livestock production, arable land and grassland surface areas were obtained from the French database AGRESTE (www.agreste.agriculture.gouv.fr/) at the scale of French departments (NUTS3), and from the FAO data base (www.faostat.fao.org/) for foreign countries. They are converted into N or P flows based on coefficients compiled from various sources (FAO, USDA databases, Lassaletta et al., 2014). Fertilizer application rates were obtained by the Unifa (Union des Industries de la Fertilisation), which provides detailed data at the regional administrative scale (http://www.unifa.fr/le-marche-en-chiffres/la-fertilisation-en-france.html).

The GRAFS approach expresses the N and P budgets on both arable land and grassland, yet N and P have very different behaviors in soil. N tends to be easily leached after its conversion into nitrate by nitrifying micro-organisms, while P is strongly sorbed onto soil particles. As a consequence, the environmental losses associated with these elements differ and budgets need to be calculated separately to integrate these specificities. For N, nitrate leaching generates water pollution. The N soil surplus is represented by the difference between N inputs to the soil through fertilizer and manure application, symbiotic N fixation by legumes and atmospheric deposition, and N export with harvested products. About 70% of the N surplus of arable land is leached to sub-surface runoff or aquifers, while a much lower fraction is leached from grassland (Billen et al., 2013).

In the case of P, erosion is the major output flux accounting for P environmental losses. P erosion from grasslands and arable lands is estimated from the soil P content cartography established for France by Delmas et al. (2015) and the erosion rates for arable lands and grasslands proposed by Cerdan et al. (2010).

The P soil balance (the difference between fertilizer and manure inputs, atmospheric deposition and export with harvested products and erosion) informs on the accumulation or depletion trend of the P stock in the soils (Garnier et al., 2015). Another discrepancy between N and P budgets rely in the gap of the N:P ratio of vegetal and animal biomass and as a consequence the need for P feed additives to sustain the livestock production. In the present study the feed additives were deduced as the unmet needs of P by the ingestion of vegetal products.

2.2.4 Evaluation of Ile-de-France's environmental imprint over its supply areas

The relative contribution to the total import to Ile-de-France of either vegetal or animal proteins, as calculated from the SitraM database, is used as an index for calculating the imprint in terms of agricultural area in each region, by considering their main orientation into either crop or livestock production. The environmental imprint of Ile-de-France was calculated only over regions that contribute to more than 1% of Ile-de-France vegetal or animal supply.

We thus define the imprint of crop production of a given region as the total resource consumption and environmental losses attributable to the portion of crop dedicated to vegetal food supply to Ile-de France. This may include some of the resources and environmental losses associated with livestock farming in so far as manure is used for crop production. Conversely, the imprint of meat and milk production is calculated by considering all resources and pollution associated with livestock farming, including those linked to crop production dedicated to animal feeding, without double counting. The details of these calculations are provided in Le Noë et al. (2017).

In some cases, animal husbandry is based on imported feed such as soybean or oil seed cakes. As a consequence, N and P imports embedded in animal feed need to be accounted for in Ile-de-France's environmental imprint. This is particularly true for regions depending on massive import of animal feed from South America (Brazil, Paraguay, Uruguay, Argentina and Bolivia). Accordingly, the environmental imprint ofSouth America vegetal production has been calculated and the share of this production imported to the regions of intensive livestock farming supplying Ile-de-France has been included in the environmental imprint of Ile-de-France.

2.3 Solid food waste generation and management

2.3.1 Food waste generation

Food waste appears at all stages of the food supply chain: transformation, transport and storage, distribution and consumption. By far the largest amount concerns the transformation of animal products, particularly slaughtering and cutting activities. Taking into account the cutting balance available for each type of livestock (Benhalima et al., 2015), as well as the N and P composition of each fraction (CIQUAL; USDA; Mello et al.,1978; Ternouth, 1990; Little, 1984), waste generation (as blood, viscera, grease, bones, etc.) associated with edible meat production can be evaluated.

Food waste generated at the latest stages of the supply chain can be evaluated by direct comparison of the above-mentioned data on food availability provided by INSEE, with the data on actual food consumption given by a national detailed inquiry organized in 2006–2007 by the Agence Nationale de Sécurité Sanitaire de l'Alimentation de l'Environnement et du Travail (www.anses.fr/), which provides detailed information on the actual ingestion of food commodities (AFSSA, 2009). Using again the N and P content given by the CIQUAL and USDA databases on food composition, the direct comparison of food availability and food ingestion has been made possible, and losses of N and P at the latest stages of the supply chain have been evaluated by subtraction.

2.3.2 Food waste management

N and P flows of food waste management were evaluated by compiling data related to food waste collection and treatment. National data on food waste production and collection are provided by surveys conducted by the French Environment & Energy Management Agency (ADEME, www.ademe.fr): a 2007 campaign characterizing domestic and economic refuse (ADEME et al., 2010) and a 2008 survey of food waste management at the household level (ADEME, 2008). The former study estimates that 75% of the collected food wastecomes from households. The latter study is only semiquantitative so several hypotheses regarding actual flows of food waste being managed on-site had to be considered. A proportion of 10% of household food waste was assumed to be managed on-site in Paris Megacity. The obligation of biowaste source separation by the largest producers is very recent and the circular that specifies these obligations dates from 2012 (Circulaire du 10 janvier 2012 relative aux modalités d'application de l'obligation de tri à la source des biodéchets par les gros producteurs (article L 541-21-1 du code de l'environnement) NOR : DEVP1131009C). Given the temporal frame used herein, we consider that only two biowaste source separations are implemented by the largest producers: oil separation in which N and P contents are considered negligible, and bone collection from slaughterhouses and butchers. For the latter, we considered that 5–10% of bones were not collected. Although some bone collection and animal processing takes place inside the city, mostly within butchers, we have considered slaughterhouses and butchers as a whole and excluded them from the perimeter of urban economic activities. Management of biowaste by economic activities and the Rungis International Market were evaluated by a local survey conducted by the French Ministry in charge of food and agriculture (DRIAAF, 2012).

Food waste treatment data were collected locally. The Ile-de-France Region Waste Management Observatory (ORDIF, www.ordif.com) has produced a survey of waste treatment facilities in the Ile-de-France region (ORDIF, 2014) that distinguishes waste treatment for Paris Megacity and waste treatment of the other Ile-de-France municipalities. Paris Megacity has one major waste treatment authority: the Joint Central Household Waste Treatment Authority for the Agglomeration of Paris (Syctom, http://www.syctom-paris.fr). It covers the densest zones of Paris Megacity and serves 54% of the population of Paris Megacity (Figure 2). Syctom is in charge of the treatment of waste and does not receive any separate collection of food waste. All food waste treated by the Syctom currently goes into three incineration plants located close to the Paris city center in Ivry-sur-Seine, Issy-les-Moulineaux and Saint-Ouen. There are 14 other incineration plants that receive the waste of Paris Megacity. Data on waste composition and waste treatment from the Syctom were analyzed in their annual activity reports and exploitation data (Syctom data, personal communication) and extrapolated to Paris Megacity.

2.4 Wastewater management in Paris Megacity

The final stage of our N and P imprint analysis stems from human metabolism: food transformation in the body and the fate of its by-products mostly as urine and feces directed to the sewers of Paris Megacity. Detailed calculations are presented in Supplementary Material.

2.4.1 Flows of N and P outside wastewater collection

Three types of losses were considered before release of N and P in sewers:

(i) human by-products of metabolism that are not in the form of urine and feces. These by-products can take three forms: integumentary and accidental losses (sweat, hair, menstruation, bleeding, etc.), breathing and N and P stocked in the body. Sutton et al. (2000) estimated that N volatilization related to sweat excretion accounts for 14 gN/cap/y, i.e. about 0.3% of N excretion through urine and feces and less than 0.1% of N loss through breathing. Taking into account that many integumentary losses reach the sewers through showering or clothes washing, a general value of 0.5% metabolized N and P not reaching the sewers was taken into account for breathing and integumentary losses. N stock in the human body is estimated at less than 0.5% of total N ingested during an individual's lifetime. P is mostly stocked in bones and is not negligible. We assume a 1% P content in the human body for a mean weight of 70 kg (INSEE), thus 0.7 kgP total stock in the body.

(ii) excretions by children strictly under 3 years of age. They were excluded from the calculation given that the intensity of their metabolism is very limited and excretions are mostly directed to waste bins via diapers. The flow of N and P of their excretions is estimated around 1% of the flow corresponding to the population of more than 3 years of age.

(iii) excretions of urine and feces that do not reach the sewer network. These excretions mostly consist of on-site sanitation systems. Adapted from Lesavre (1995), 2% of the population of Paris Megacity has been considered to use on-site sanitation or open urination and defecation.

2.4.2 Flows of N & P in wastewater

The flows of N & P in Paris Megacity wastewater were calculated on the basis of operational data provided by the SIAAP (Syndicat Interdépartemental d'Assainissement de l'Agglomération Parisienne, www.siaap.fr). The SIAAP is a public institution in charge of wastewater transport and treatment and it covers 85% of the population of Paris Megacity (Figure 2). The SIAAP operates six wastewater treatment plants including Seine Aval, located on the municipality of Achères, 20 km to the northwest of the center of Paris, which treats the wastewater of 53% of the population of Paris Megacity. About 35 other wastewater treatment plants treat the remaining 15% of the population of Paris Megacity (see http://assainissement.developpement-durable.gouv.fr/ for detailed information) and their operational results do not significantly differ. We thus extrapolated the results obtained on the basis of

SIAAP operational data to the whole population of Paris Megacity. We used SIAAP operational data between 2004 and 2014 (SIAAP, personal communication). The year 2013 was selected for the results of the treatment plants because it was the first year when routine denitrification in Achères was in full operation. It was also considered representative in terms of rain events and collection efficiency.

Discharges from the sewer network were calculated as the sum of dry weather discharges and rain weather discharges as combined sewer overflows. These data were evaluated from the sanitation master plan of the SIAAP area approved in 2017 (SIAAP, personal communication). N & P discharges to the sewer network unrelated to human metabolism were calculated by the difference between metabolic inputs, sewer discharges and treatment plant inputs. Food waste inflows were estimated on the basis of grey water composition (Deshayes, 2015; Larsen et al., 2013, chap. 17; Chaillou et al., 2011). N and P discharge in rivers and N and P content in sewage sludge were calculated on the basis of SIAAP data. N_2 emissions were deduced by subtraction and N_2O emissions were calculated from measurements taken at the Achères wastewater treatment plant (Bollon et al., 2016a and 2016b) and extrapolated to Paris Megacity. SIAAP sludges are either incinerated or recycled in agriculture through direct spreading or composting. Sludge spreading plans were examined to quantify and localize N and P recycling on agricultural lands.

Figure 2.

3. Results

3.1. The agro-food system supplying Paris Megacity

3.1.1. Food supplying areas

The analysis of the transport matrix concerning the 33 French agricultural regions and foreign countries reveals strong spatial segregation between regions supplying vegetal or animal products to Paris Megacity.

Five regions currently provide 80% of the Paris Megacity supply of vegetal proteins, namely Ile-de-France (55%), Champagne-Ardennes-Yonne (8.9%), Loire Centrale (8.4%), Picardie (4.5%) and Eure-et-Loir (3.5%). Those regions are highly specialized in field crop production (Le Noë et al., 2016, 2017) and their production of animal proteins is negligible. In view of their spatial distribution around Paris Megacity (Figure 3), the whole area is hereafter called the “Central Paris Basin” and classified as a “crop farming” region.

The animal protein supply is much more dispersed: 19 French regions contribute more than 1% each and together supply 55% of Paris Megacity animal proteins. Three of these regions – Bretagne, Loire Aval and Manche – account for 32% of the Paris Megacity animal protein supply. They are strongly specialized in intensive livestock production, which depends on massive imports of animal feed from South America (Le Noë et al., 2016, 2017). As those regions are spatially distributed in western France (Figure 3), the whole area is hereafter called the “Great West” and is classified as an “intensive livestock farming” region. On the other hand, the 16 remaining regions total 23% of the animal protein supply. They are much less specialized in one or another type of production, but they occupy a larger agricultural area; in addition, the proportion of permanent grassland is largely equivalent to that of arable land. These features characterize these regions as “mixed crop and livestock farming.” We call the “Great East” a territory formed by six regions (Loire Amont, Grande Lorraine, Cantal-Corrèze, Ain-Rhône, Isère-Drôme-Ardèche and Bourgogne), which supply 13% of Paris Megacity animal proteins. Furthermore, various foreign countries contribute to the animal food supply (Figure 3). Their local environmental imprint is not directly calculated because of the lack of information regarding the functioning of the agro-food system and the uncertainties regarding their N and P environmental losses. Yet based on literature data (Billen et al., 2014) we have classified foreign countries as being close to the intensive livestock farming or mixed crop and livestock farming typologies. This allows us to estimate the share of animal proteins provided by intensive livestock farming regions or mixed crop and livestock farming regions (Figure 5).

Regarding imports of feed to the Great West region from South America, they represent 67% of the 302 ktN/y imported to France. These imports are undoubtedly essential to support cattle breeding in the Great West, which satisfies about one-third of Paris Megacity animal protein requirement; hence South America takes a significant, yet indirect, part in the food supplying area of Paris Megacity that we define as a “soybean cultivation” area.

In summary, our analysis reveals four distinct typical areas contributing to the Paris Megacity food supply, each with its own agricultural system/orientation. These regions are (i) the Central Paris Basin, specialized in crop farming; (ii) the Great West with intensive livestock farming, strongly dependent on (iii) South American countries as feed suppliers; and (iv) the Great East with mixed crop and livestock farming (Figure 4a–h).

Figure 3.

3.1.2 The agro-food system of the supplying territories

To gain better insight into the agricultural metabolism of each of the four types of territory supplying Paris Megacity, we established the full GRAFS diagram of N and P flows across their agricultural systems (Figure 4a–h). The GRAFS representations highlight the fact that all regions use high inputs of synthetic N and P fertilizers. This is especially true for the Central Paris Basin region since there is no other significant source of N and P inputs to agricultural areas, in the absence of livestock. The very high crop production even leads to a negative P soil budget (i.e., a depletion of P) on cropland. The very specialized Great West region is characterized by a strong dependency on feed import, low grassland area and intense N surplus from arable land, the source of environmental losses. In contrast, the Great East region is characterized by a large grassland area, food and feed self-sufficiency and smaller surplus on arable land. Finally, South America is also defined by large grassland areas, food and feed self-sufficiency, but shows a very export-oriented metabolism since 58% of its vegetal production is traded internationally.

Figure 4.

3.1.3 Environmental imprint of Paris Megacity food supply

As stated above, the imprint of Paris Megacity food consumption in each supplying area is defined as the resources consumed and the environmental nutrient losses, which are attributable to the food supply of Paris Megacity. Table 2 summarizes the calculated imprints over the four main supplying areas which contribute 62% of the total protein supply of Paris Megacity. Overall, this agricultural area is estimated at about 2.5 million ha of which approximately one-third are grassland areas, almost all located in the mixed crop and livestock farming area. When these absolute numbers are reduced to the population of Paris Megacity, it appears that 0.26 ha is required for this part of the food supply per inhabitant (62%). Of these, only 0.011 ha, less than 5%, is dedicated to the supply of vegetal proteins, the remaining being mostly devoted to meat and milk production. The total nitrogen imprint of these agricultural activities across these areas is estimated to be a surplus of 114 ktN/y with about one-fourth of this surplus in grassland and a NH_3 volatilization of 38 ktN/y. Yet it is necessary to take into account that environmental consequences of the N surplus on arable land and on grasslands are significantly different. On arable land, about 70% of the N surplus ends up in the hydrosystem (Billen et al., 2013). In contrast, N inputs contributing to the N surplus in grassland, below a threshold of 100 kgN/ha/y, keep accumulating in the soil organic matter pool (Billen et al., 2013). Accordingly, the surplus observed in grassland should not necessarily be viewed as a negative environmental impact, as it accompanies the increase of the soil organic matter pool. The P eroded from those areas feeding Paris Megacity is estimated to reach 3.2 ktP/y with 95% derived from arable land. However, it is difficult to determine the amount of P reaching the surface water because eroded particles can accumulate in downhill and riparian sectors.

More specifically, it appears that the mixed crop and livestock farming area is the most costly in terms of the surface required to feed Paris as well as of N and P fertilizers and N surplus on arable land. However, this area is almost self-sufficient since it requires low net imports of feed from other regions to sustain its livestock production. In contrast, the intensive livestock farming area imports a substantial amount of feed from South America, making these two areas part of a same system. With this in mind, it appears that the environmental imprint of Paris Megacity is not so different for both systems and is higher in terms of P surplus on arable lands over the intensive livestock farming/soybean cultivation regions.

Table 2. Estimation of the environmental imprint of Paris Megacity over its main supplying areas.

	Category	**Central Paris Basin**	**Great West**	**South America**	**Great East and similar***	**Total**
Surface, ha	*Cropland*	109 206	384 098	271 940	652 620	1 417 863
	Grassland	-	116 778	-	840 686	957 464
N fertilizers, ktN/y	*Cropland*	16	17	16	36	85
	Grassland	0.1	3.8	-	25	29
Feed import, ktN/y	*Livestock*	-	36	-	4.2	40
NH_3 emission, ktN/y	*Livestock*	-	14	-	24	38
N surplus, ktN/y	*Cropland*	4.7	26	18	26	74
	Grassland	0.5	2.8	-	30	33
P fertilizers, ktP/y	*Cropland*	1.5	1.9	7.8	3.7	11
	Grassland	0.5	0.1	-	2.9	3.5
Soil P accumulation (or depletion), ktP/y	*Cropland*	-1.2	5.1	0.7	1.7	6.3
	Grassland	-	0.1	-	1.9	2
Feed import, ktP/y	*Livestock*	-	5.6	-	1.4	7.0
Feed additives, ktP/y	*Livestock*	-	5.7	-	7.1	12.8
P erosion, ktP/y	*Cropland*	0.5	1.1	No value	1.4	3.0
	Grassland	-	0.03		0.2	0.23

*All French mixed crop and livestock farming regions contributing more than 1% of the animal food supply of Paris Megacity.

To summarize, Figure 5 shows the main flows of N and P resources mobilized and/or lost to the environment attributable to the animal and vegetal food supply of Paris Megacity.

Figure 5.

3.2 Food waste flows in Paris Megacity

3.2.1. Waste generation in the food transformation industry

Wastes are generated along the entire supply chain from agriculture production to the final urban consumer. The largest proportion of these wastes concerns the meat slaughtering and cutting stage.

The transformation of living animals into edible products generates a huge amount of waste evaluated at 1.1 kgN per kgN in edible form for N and 8.2 kgP per kgP for P. The very high level of waste generated in terms of P is related to the high P content of bones. This represents a per capita production of slaughtering and cutting wastes for Paris Megacity of 3.9 kgN/cap/y and 0.8 kgP/cap/y, respectively.

3.2.2. Food waste at the retail and consumer level

The data on food commodity availability (INSEE), expressed in kgN/cap/y, have been stable since 1990 after an overall increase of the values since the 1950s, especially for animal products. Compared to these, the food ingestion data collected by AFSSA (2009) show a per capita consumption approximately 35% lower when expressed in N or P. This difference can be attributed to waste production between the retail and the final ingestion stage. Evaluation of these losses per food commodity group (Table 3) shows figures varying from 19% for cereals to 50% for fruits and vegetables (in terms of N content)**.** Overall, this leads to a per capita domestic waste generation of 2.4 kgN/cap/y and 0.24 kgP/cap/y (excluding bones).

Table 3. N and P composition of food supply per capita (INSEE, 2001) and actual consumption (AFSSA, 2009).

Nitrogen	Phosphorus

	Supply kgN/cap/y *(% of total supply)*	**Consumption** kgN/cap/y *(% of total consumption)*	**Losses** kgN/cap/y *(% of total losses)*	**Supply** kgP/cap/y *(% of total supply)*	**Consumption** kgP/cap/y *(% of total consumption)*	**Losses** kgP/cap/y *(% of total losses)*
Seafood	0.7	0.3	0.4	0.05	0.02	0.03
Dairy and eggs	1.7	1.0	0.7	0.21	0.13	0.08
Meat	2.8	2.1	0.7	0.18	0.14	0.04
Fruits & vegetables	0.7	0.4	0.3	0.11	0.05	0.06
Cereals	1.3	1.1	0.2	0.11	0.09	0.02
Total animal	**5.3 *(72)***	**3.5 *(71)***	**1.8 *(75)***	**0.45 *(67)***	**0.29 *(67)***	**0.16 *(67)***
Total vegetal	**2.0 *(28)***	**1.4 *(29)***	**0.6 *(25)***	**0.22 *(33)***	**0.14 *(33)***	**0.08 *(33)***
Total	**7.3**	**4.9**	**2.4**	**0.67**	**0.43**	**0.24**

3.2.3 Food waste management

The N and P food waste flows in Paris Megacity are illustrated in Figure 6a and b. Apart from bone collection and other recovery of animal waste, the main form of reuse is represented as on-site food waste disposal by households. According to ADEME (2008), this on-site disposal mainly takes the form of animal feeding (pets and wild animals). Since excretions of urban animals are seldom recovered, animal feeding ultimately adds to the environmental losses of N and P in the city. Composting food waste is a minor form of on-site reuse. It is of course more common in the parts with the lowest population density. Only about 100 collective composters were counted in the Paris city center in 2012 (www.paris.fr, compost section). We can therefore assume that less than 1% of household food waste is composted in Paris Megacity's densest areas. However, when food waste is composted, it is used for garden food production in two cases out of three, which therefore contributes to effective N and P recycling. Food production inside Paris Megacity is nevertheless considered negligible.

In the end, more than 80% of food waste is collected by municipalities together with other residual waste. Whereas green waste from the garden is often collected separately, only one waste treatment plant, located in Saint-Ouen-l'Aumône, receives source separated food waste and composts it in Paris Megacity (ORDIF, 2014). Three other waste treatment plants in Paris Megacity carry out mechanical-biological sorting of residual waste for composting or methanization. However, they receive less than 1% of the total Paris Megacity food waste production.

In Figure 6a and b, economic activities represent all places where food waste is handled out of the households: markets, supermarkets, restaurants, canteens, bakeries, etc. (except for activities leading to bone collection as specified in section 2.3.2). The Rungis International Market, reportedly the largest market of agricultural products in the world, performs food waste composting or methanization, but this accounts for less than 1% of Paris Megacity food waste production. Except for collection of bones within butchers, other economic activities mostly rely on mixed residual waste collection for food waste disposal.

Finally, incineration is the prevailing destination of Paris Megacity food waste. It entails negligible releases of reactive N and P in the environment, but it does not achieve any form of N & P reuse. N content in food waste turns back into the atmosphere as N_2. P stays in the bottom ash and is stabilized in clinker. Clinker is mostly used as construction material, which does not allow specific P reuse.

Figure 6.

3.3 Wastewater flows in Paris Megacity

Compiled results of N & P flows related to human metabolism and wastewater management are presented in Figure 7a, b. Apart from P stocking in bones, N & P ingestion overwhelmingly ends up in wastewater and 98% of it is collected by sewer networks. The impact of commuting people is very small: the balance is in favor of people coming daily to Paris Megacity to work, with more than one-third coming from outside the Ile-de-France region, but most of their N & P excretion takes place at home and their final contribution to N & P flows in Paris Megacity is around 1%. The largest impact comes from the inhabitants of Paris Megacity leaving the city for holidays, which on average accounts for 26 days per person per year, i.e., 7% of Paris Megacity inhabitants are absent on a yearly basis. Tourists coming to Paris Megacity do not offset these departures and increase the population of Paris Megacity by only 4%. In the end, the population census in Paris Megacity is evaluated at 10.6 million inhabitants, but only 9.8 million inhabitants over 3 years old actually excrete N & P on this territory as an annual average.

Direct dry weather discharges from the sewer network to rivers that are identified in the sanitation master plan of the SIAAP area are very low and account for only 25,000 population equivalents. Most losses occur during rain events from combined sewer overflows and are estimated to around 3% of total inputs.

The proportion of P collected in the sewers that is not related to excretion or food waste is much higher than for N, mainly because of the use of P in detergents. It accounts for 30% of the total collected phosphorus in 2013, i.e., 0.17 kgP/cap/y. In the last 10 years, this figure has been steadily decreasing by about 0.03 gP/cap/y due to bans of P in detergents. It is expected to continue decreasing with a new limitation on P in dishwashers that will come into effect in 2017 by application of EU regulation No. 259/2012 of the European Parliament and of the Council of 14 March 2012. Total P discharge in the rivers represents 18% of total P entering the networks, but only half of the sludge is directly spread on agricultural land or composted. The other half is incinerated in various facilities and P is not recovered from incineration ashes.

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 N_2O. Kampschreur et al. (2009) reported a considerable range of uncertainty regarding N_2O emissions in wastewater treatment plants, varying from 0.05% to 25% of N-load. Recent measurements at Achères wastewater treatment plant lead to a 2% ratio. N recycling to agriculture is negligible. Total N discharge in the river from the area's wastewater treatment plants respects the UWWT Directive regulatory threshold of 30%, but the effective global rate of N river discharge from the wastewater system is about 38%. For a megacity like Paris, this means that the metabolic N of about 4 million people is discharged daily into the Seine River in a reactive form (mostly NO_3^-).

Figure 7.

3.4 Overview of the nitrogen and phosphorus imprint of human metabolism in Paris Megacity

The results on the biogeochemical imprint of human metabolism in Paris Megacity from all three subsystems of agro-food production, waste management and wastewater management are compiled and summarized in Figure 8a and b. The imprint for other agricultural regions than the four supply areas studied was deduced by extrapolation, considering the same characteristics for these regions as for their corresponding studied counterpart. N and P loads to the wastewater management that are not directly related to food and excretion were also removed and subsequent flows proportionally recalculated. They allow a general vision of this imprint that contributes to characterizing a socioecological regime (Fischer-Kowalski and Haberl, 2007) as discussed in section 4.2.

Figure 8.

4. Discussion

4.1 Quality of results and uncertainties

The majority of the flow accounts are based on local data, mostly provided by French administration surveys and inventories. This method presents the advantage and the originality of providing an accurate overview of the biogeochemical imprint of human metabolism in Paris Megacity rather than a theoretical estimation of its imprint based on literature data. This advantage is counterbalanced by two main drawbacks: (i) the high dependence on the reliability of the locally available data and (ii) the low availability of results expressed in N and P content in local data.

The uncertainties concerning the GRAFS flows are extensively discussed in Le Noë et al., 2017. In the present study, the P imprint of Paris Megacity has been calculated on the basis of the N imprint by using of N/P ratios. It leads to a slightly unbalanced P budget showing a 21% to 38% gap between inputs and outputs on figure 5 and figure 8.

Regarding our N & P flow calculations in the waste management subsystems, their reliability is difficult to establish. Most data on food waste are given in kilograms of food waste, but our approach is based on N and P to trace the actual nutrients contained in food necessary for human metabolism. Figures in kilograms of food waste are difficult to interpret given the variability of the moisture in food waste (some of the collected studies take liquids into accounts and others exclude them). Moreover, it is difficult to accurately analyze the composition of a trash bin and its specific content in food waste (ADEME et al., 2010; Syctom data). All types of waste are usually mixed in residual waste bins and it is difficult to sort them again. However, Syctom data enable the calculation of N and P content of a sample of collected waste bins and we found values of 1.9 kgN/cap/y and 0.35 kgP/cap/y. If we consider that most N and P comes from food waste, these values tend to show a correct estimation for N and P collected in waste bins. Data on P could not be cross-checked with local analysis of bottom ash since this element is not measured on Syctom ash. Calculated values of N and P losses between the slaughter/cutting and packaging steps are taken into account in the GRAFS representation, but the fate of these flows remains uncertain. Yet a complete analysis of P recovery and recycling from waste is provided by Senthilkumar et al. (2014). This study was conducted at the national scale, so it is difficult to convert it to local food waste management considerations.

Application of the literature values on P content in bottom ash in France (Aouad et al., 2006) gives a total production of 0.24 kgP/cap/y for Paris Megacity, as compared to 0.31 kgP/cap/y in our calculations. N can unfortunately not be measured after combustion since it eventually goes back to the atmosphere as N_2.

N and P excretion values based on AFSSA (2009) ingestion data are compatible with literature values on the excretions of Westerners (Larsen et al., 2013, chap. 17) with a 4% difference on N values but a higher 25% difference on P values.

Finally, data on wastewater seem to be the most reliable since N and P are actually measured by wastewater operators as monitoring variables. Uncertainties on the values of losses in the sewer network are the most difficult to estimate. Dry and wet weather losses are given by the sanitation master plan of the SIAAP area, but it is by nature very difficult to estimate the losses that are not known by the wastewater authorities. In particular, two sources of losses have not been taken into account in these calculations: ground infiltration of N and P from leaking sewers and discharges by the smallest sewers. However, the good correlation between N and P originating from human excretion and N and P arriving at the wastewater treatment plant tends to confirm that estimated losses by the sewer network of Paris Megacity are acceptable.

Interannual variability of quantities of N per capita received by the SIAAP in recent years is quite low (±5%) and 2013 is in the middle of this variability range. The decrease of P values is known to stem from the limitation of P use in detergent and confirms the validity of the measured values.

As a whole, the data used in this study come from a variety of sources with some more reliable than others and, according to Courtonne et al. (2015), can be classified as such: water quality measurements > official statistics available for the long term (e.g., agricultural data) > N and P content coefficient > recent declaration-based statistics (e.g., biowastes).

4.2 The main characteristics of the water-agro-food socioecological regime of Paris Megacity

4.2.1 A minimized local imprint on Paris Megacity area

The local imprint calculated through the discharge of N and P on Paris Megacity area is minimized by intensive treatment units. P in incinerated food waste ash is stabilized in construction materials and food waste N mainly goes back to the atmosphere as harmless N_2. Less than 20% of the P excreted by human metabolism ends up in the Seine, which is compatible with international regulations applied to the Seine. Given the population of Paris Megacity, it still represents an imprint in absolute figures of 1.3 10^6 kgP losses per year. N releases from the wastewater system account for 38% of human excreted N. Although its main form is nitrate, which does not contribute to major local disruptions in the Seine inside Paris Megacity, N released as ammonium and nitrites are still at high levels compared to the expected level for good ecological potential (Romero et al. 2016), as required by the WFD.

The wastewater authorities of Paris Megacity are currently undertaking or scheduling complementary intensive pollution mitigation works. The Seine in the Paris city center only has a monthly minimum flow with a 5-year return period of 94 m^3/s (DRIEE-IF, 2014), which leaves only 830 L/cap/day of dilution capacity. The WFD threshold of 0.5 $mgNH_4^+$/L in the Seine River thus requires at least 98% efficiency in reduced N removal. Despite reaching the limits of the technical feasibility of centralized wastewater treatment, ammonium concentrations in the river should be lowered in the coming years to values compatible with the WFD. On the other hand, nitrite concentrations remain an issue. Even with advanced wastewater treatment, the compatibility of the centralized environmental impact of treated water discharge with the preservation of the local environment remains an issue in a megacity. The expected decrease of the Seine River flow in the coming years due to climate change will challenge this paradigm even more.

Moreover, two main forms of N release have an imprint at a larger scale than Paris Megacity area: more than 20 10^6 kgN annual export of N to the estuary, mainly in the form of nitrates, and about 400 $ktCO_2eq$ annual N_2O emissions from the wastewater treatment plants.

4.2.2 Poor reuse of nitrogen and intermediate reuse of phosphorus

Urban reuse of N and P flows is assessed by their recovery rates. The N cycle is the most extreme in terms of linear management since only 3% of the N entering the city (7.3 kgN/cap/y) goes back to the agro-food system (0.2 kgN/cap/y), whereas the agricultural production system requires about 570% of the N (37.4 kgN/cap/y) that is eventually supplied as food (6.6 kgN/cap/y). The fate of P is more contrasted. First, bone collection and other agro-industrial waste reuse enable recycling 75% of P (Senthilkumar et al., 2014). Second, the overall recycling rate of the wastewater system is only 41% and urban food waste recycling is negligible. Thus 70% of the P of urban food (0.79 kgP/cap/y) ends up unrecovered in clinker (0.48 kgP/cap/y) or water discharges (0.08 kgP/cap/y).

Sewage sludge recycling is quite problematic for Paris Megacity: low acceptance of sewage sludge by farmers and limitations on the use of sewage sludge in agriculture lead Paris Megacity to export its sludges relatively long distances: around 200 km for direct sludge spreading and 300 km for sludge composting. With half of the sewage sludge of Paris Megacity being incinerated, these figures would probably be higher if sludge spreading was chosen for the whole megacity.

The geographic spread of food supply and urban residue reuse appears dissymmetrical. There is a political commitment not to exceed 200 km for the spreading of sewage sludge (cf. Public Debate on Achères wastewater treatment plant in 2007, e.g., Question & Answer No. 80: http://cpdp.debatpublic.fr/cpdp-seineaval/participer/reponses-questionsdcfd.html?id=4), whereas the agro-food system of Paris Megacity is based on 2.7 10^5 ha of soybean cultivation in South America and 5 10^5 ha of intensive livestock farming in the Great West, mostly located more than 300 km from the Paris city center.

This effect is exacerbated by the high concentration of more than 10 million people. It is also worth noting that most food waste recycling processes documented by ORDIF (2014) in the Ile-de-France region concern periurban areas located outside Paris Megacity. The scale of Paris Megacity most probably contributes to the implementation of processes poorly connected to agricultural recycling also in food waste management.

Our regionalized approach also makes it possible to calculate the amount of N and P that is recycled through sewage sludge spreading or composting on agricultural lands that supply food to Paris Megacity (an effective nutrient recycling loop). This figure is totally negligible for N, given the low amount of N in sewage sludges. For P, the figure also remains very low and we estimate that 0.03% of the total vegetal P ingested by the inhabitants of Paris Megacity comes from effective recycling of excreted P. Around 80% of the recycled sludges are effectively spread on the Paris Central Basin that supplies Paris Megacity with vegetal food, but this region is largely dedicated to the export of cereals, so the recycled P of Paris Megacity is mostly exported. Assuming that three-quarters of the daily ingestion of 100 g of bread per person per day (AFSSA, 2009) is in the form of the "baguette", we can still estimate that, on average, the P of 1,000 daily "baguettes" ingested by the inhabitants of Paris Megacity, out of more than 3 million, comes from direct recycling of the P contained in their urine and feces.

4.2.3 The externalized imprint of Paris Megacity

With the environmental imprint of Paris Megacity becoming less and less significant on the urban area itself, Paris Megacity has nearly completely externalized the environmental imprint of human metabolism on agricultural lands. It makes it largely invisible for urban dwellers, seldom conscious that pollution in South America or in the Great West is directly related to their consumption of food.

As stated above, the food supply of Paris Megacity is supported by four areas characterized by four distinct metabolisms. For its vegetal food supply, Paris Megacity is almost only provided by a close hinterland specialized in crop production. For its animal food supply, Paris Megacity relies on two quite different systems, namely the Great West, characterized by intensive livestock farming and importing large amounts of feed from South America, and a more diffuse area of mixed crop and livestock farming.

When looking only at the absolute figures, the imprint of the vegetal product supply to Paris is much lower than the impact of the intensive livestock farming coupled with its South American feed supplier's area, which is itself similar to that of the mixed crop and livestock farming areas. However, when compared with the corresponding surface area involved, the figures of nutrient losses per hectare show a different picture, where the large mixed crop and livestock farming areas are characterized by much more diluted losses than the intensive livestock farming area and even than the specialized crop farming area, with lower impact on hydrosystems. For instance, the N leaching reaches 37 kgN/ha/y in the intensive livestock farming area compared to 30 kgN/ha/y in the specialized crop farming area and 12 kgN/ha/y in the mixed crop and livestock farming area. The P erosion expressed per hectare is 4.5, 2.4 and 1.0 kgP/ha/y in the specialized crop farming, the intensive livestock farming and the mixed crop and livestock farming system, respectively.

Accordingly, although the environmental imprint of Paris Megacity appears to be strong on the mixed farming system, we believe that the dilution of the calculated values over a large surface area leads to the least impact on the surrounding agro-ecosystem.

This externalized imprint of Paris Megacity can also be noted on the quality of water resources for the drinking water supply. A large number of wells are being de-commissioned in France, with about one public well closed every week due to N contamination, particularly in Ile-de-France (Ministère de la Santé, 2012). Most bodies of groundwater around Paris and in the Central Paris Basin appear in the 2015 Seine River basin management plan to have a poor chemical status, mainly because of their high concentration in nitrate. On the other hand, Paris Megacity mainly relies on treated surface water, less contaminated by nitrates, for its water supply.

4.2.4 The central issue of human metabolism

As mentioned above, human metabolism appears to be the key element around which the whole water-agro-food system is organized since ingestion of food and the resulting excretion are one of the core, vital drivers of sustaining human life. The intensity of the megacity's socioecological regime depends enormously on the human diet. Two-thirds of the ingested N and P come from animal products, but they account for more than 90% of N and P agricultural inputs and more than 95% of surfaces dedicated to food production. Depending on the diet of an inhabitant of Paris Megacity, the contribution of each subsystem to the global imprint can be significantly different. For example, N leaching from crop farming lands is 0.4 kgN/cap/y whereas N discharge in water from the wastewater management is 1.9 kgN/cap/y. It means that the N imprint on water bodies of a Paris Megacity inhabitant following a vegan diet could be higher at the wastewater treatment plant than on the agricultural lands feeding him.

The total amount of ingested N and P is also an important characteristic that impacts all subsystems of the water-agro-food system. Compared to the needs of N ingestion of 3.3 kgN/cap/y (WHO et al., 2007), Paris Megacity's mean diet currently contains 150% of this level.

4.3 Changes in the imprint of human metabolism in Paris Megacity

The description provided above of the current environmental imprint of the human metabolism in Paris Megacity can trigger the conception of possible optimization paths toward a more sustainable food supply and waste management.

4.3.1 Possible optimization paths

According to our analysis, agriculture, through resource consumption and nutrient release to the hydrosphere and the atmosphere, produces by far the largest imprint of urban metabolism, compared to waste and wastewater management. Yet since the late 1980s considerable effort has been expended to optimize agricultural practices and fertilizer use in the scope of what is called “reasoned agriculture”. This effort has succeeded in stabilizing agricultural N pollution to a level that is, however, still incompatible with good ecological status of most water bodies (Passy et al., 2016; Romero et al., 2016), not only because of the slow response of long residence time soil and aquifers nutrient pools, but also because of the unavoidable losses generated by intensive and specialized chemical agriculture (Billen et al., 2016).It is clear, therefore, that deep structural changes of the agro-food system, beyond the mere optimization of agricultural practices, will be necessary to further reduce the environmental imprint of Paris Megacity food supply. One of the most striking characteristics of the current agricultural system supplying Paris Megacity is its spatial specialization into either crop farming or livestock farming areas, with very few connections between them (Le Noë et al., 2016). Inverting this specialization trend and reconnecting crop and livestock farming is likely to be the best option for reducing agricultural nutrient pollution (Lemaire et al., 2014; Bonaudo et al., 2014; Garnier et al., 2016; Billen et al., 2016). Exploring scenarios, several studies at the regional and global scale have demonstrated that a reduction in animal protein in the diet, while reconnecting crop and livestock production, would clearly reduce ground and surface water nitrate contamination, major changes that are compatible with organic farming (Billen et al., 2015; Garnier et al., 2016; Lassaletta et al., 2016).

The present study also showed that by far the largest imprint of Paris Megacity food supply is related to livestock breeding rather than to vegetal production. This implies that any reduction of the proportion of animal products in the human diet, as advocated by the 2009 Barsac declaration (http://www.nine-esf.org/barsac-declaration), would have a tremendous lever effect on the agricultural imprint. Lowering the total quantity of ingested proteins is also not only possible but recommended by French health authorities (Haut Comité de la Santé Publique, 2000). It would trigger a decrease in the intensity of the imprint of Paris Megacity on agricultural land as well as for the wastewater treatment. If the current population increase of approximately 0.5% per year continues, reducing by half the excess in the total quantity of proteins ingested with respect to official recommendations would make current wastewater treatment plants compatible with the development of Paris Megacity for the next 35 years.

Food waste management should be substantially optimized in the coming years. Two recent laws address biowaste management in France: (i) the above-mentioned legislation on large biowaste producers (section 2.3.2). Since the beginning of 2016, all producers of more than 10 tons on biowaste per year (e.g., a canteen serving 300 people per day) are required to specifically reuse their biowaste. (ii) The law on energetic transition (“Loi n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte”). This law requires that waste management public services should enable all citizens to reuse their biowaste by 2025 (Art. 70. V. I.4°). In this perspective, experimental collection of biowaste has started in 2017 for 157,000 inhabitants of the Paris city center. Unfortunately, these laws are mainly carbon-oriented and do not point to N and P recovery as an important issue. The future trajectory of food waste N and P in Paris Megacity will then depend not only on the effective application of these laws, but also on the actual implication on N and P in the general concept of "biowaste reuse."

Concerning N and P in wastewater, this study reveals that N management has not been considered in terms of its imprint and reuse of P is limited. No legislation in France mentions resource recovery of N and P in wastewater and the Sustainable Development Goals adopted by the United Nations in 2015 on sanitation do not mention any stake of resource recycling. Since 1 January 2016, Switzerland is reported to be the first country in the world to have made P recycling from sewage sludge mandatory (http://www.phosphorusplatform.eu/platform/news/1061-switzerland-makes-phosphorus-recycling-obligatory). In countries with a nutrient deficit in soils, the potential for using human waste, especially excreta, has been shown to be high (e.g., in Uganda, Lederer et al. 2015). In developed countries, many studies have explored the possibility of evolving wastewater management through source separation of human excreta or changes at the wastewater treatment plant (Villarroel Walker et al., 2014; Wilsenach et al., 2003; Larsen and Lienert, 2007). Some European districts have already implemented source separation of human excreta (see e.g. the case studies by the Sustainable Sanitation Alliance, www.susana.org/en/resources/case-studies). For instance, urine separation has specifically been studied at the scale of France, Paris Megacity and in Paris-Saclay, a new district of Paris Megacity: although already implemented in Paris at the beginning of the 19th century, reintroducing urine source separation requires the implementation of French pilot projects to test the possibility of its larger-scale and longer-term development (Caby, 2013; Besson et al., 2015;; Crolais et al., 2016).

4.3.2 The limits to minimizing the imprint of Paris Megacity

This study shows that there is considerable room for improvement in minimizing the biogeochemical imprint of Paris megacity. Nevertheless, it has to be kept in mind that our approach based on N and P flows is necessarily limited in its findings. Describing the water-agro-food system of Paris Megacity solely through N and P flows leaves aside many other aspects of this system: water consumption, greenhouse gas emissions, energy requirements, sanitary issues, etc. Moreover, accounting for flows in terms of N and P does not take into consideration the specific form in which N and P are embedded and the constraints related to the management of these flows (fertilizers, manure, food, food waste, human excreta, etc.). Nonetheless, given the importance of the stake of proper management of N and P, in terms of both resource management and environmental disruptions, the low efficiency of water-agro-food system of Paris Megacity remains striking. Urban and agricultural N and P management appears mostly disconnected, which reflects disconnected sectorial policies of food production, waste and wastewater management. Efficient N and P management of the water-agro-food system of Paris Megacity appears to be a neglected part of the equation and this study highlights this point. As stated by Rosemarin (2010) for P and Sutton et al. (2011) for N, the importance of correct management of N and P flows is currently an outcome of the research led by the scientific community, but awareness and transposition into policies is not yet fully effective, although several improvements are on-going, as stated in section 4.3.1. An integrative analysis appears useful for supporting decision-making and integrating social, health and economic issues into the urban-rural metabolism framework (Kennedy et al., 2011).

Much is still expected from the agricultural sector to reduce N's environmental impact on water contamination despite the implementation of a number of agricultural practice measures (reduction of fertilization, implantation of grassed strips and catch crops, etc.) that at best have stabilized nitrate concentrations. Concerning P, although its application as a fertilizer has been reduced, its content in soils is still high and requires avoiding its losses to the environment (e.g. by limiting erosion).

The improvement of urban residue management requires shifting waste and wastewater treatment into a paradigm of integrated resource management. For this purpose, Wilsenach et al. (2003) conclude that dilution is never a solution, advocating source separation of flows. If its implementation is partly on its way for solid waste, implementation of wastewater source separation in Paris Megacity implies more fundamental changes in the design of houses and the sewerage system. Its large-scale deployment can only be considered over the long term and constitutes a major obstacle to short-term improvement of the imprint of Paris Megacity.

Eventually, minimizing the imprint of Paris Megacity requires forging an integrated nutrient policy, linking agricultural and urban policies. If this process seems to be on its way in some countries (see e.g. SRU, 2015), France and Paris Megacity currently lack an integrated N and P policy: the development of such a policy will be a crucial step to make the imprint of Paris Megacity compatible with the stakes of N and P resource availability and of their environmental impact.

5. Conclusion

This case study highlights the particularities of megacities in terms of their water-agro-food socioecological regime. Megacities attract huge amounts of nutrients, but paradoxically they are not, at present, able to return them to agricultural systems, an option that was hotly debated during the 19th century when urban waste and wastewater management was founded (Barles, 2005). In developed countries, these megacities limit their local N and P impact using technological solutions. This paradigm is embedded in the linear metabolism that characterizes the industrialized and post-industrialized societies to which they contribute, resulting in the externalization of the urban biogeochemical imprint. These characteristics are particularly well illustrated in Paris Megacity. Most of the environmental impacts that concern the local scale are managed within a paradigm of pollution treatment in incineration plants and wastewater treatment plants but disconnected from resource management issues in the four main agricultural supply areas of Paris Megacity. Moreover, given the respective size of Paris Megacity and the Seine River, centralized management of water pollution mitigation limits the capacity of Paris Megacity to have a sustainable environmental impact.

N and P management shows contrasted patterns. The P imprint of Paris Megacity requires optimizing its efficiency in P use and minimizing soil storage, soil erosion and losses in incineration ash, which represents about seven times the P actually ingested. Urban N recycling conceals considerable room for improvement with a current recycling rate of 3%. N release into the environment is a major concern, mostly in agriculture but also in wastewater treatment, with an overall imprint of nearly four times the N actually ingested.

The water-agro-food system of Paris Megacity for the most part is not in phase with the stakes of integrated N and P management. The results reported herein call for the development of an integrated nutrient policy that would transcend the sectorial policies of agriculture as well as solid waste and wastewater management. The global vision of the N and P imprint that we have developed could help pave the way for establishing socioecological trajectory scenarios that would improve the sustainability of Paris Megacity.

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