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1 The biogeochemical imprint of human metabolism in Paris Megacity: a 2 regionalized analysis of a water-agro-food system

3

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26 Keywords

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

28

29 Abstract

30 Megacities are facing a twofold challenge regarding resources: (i) ensure their availability for a growing urban
31 population and (ii) limit the impact of resource losses to the environment. This paper focuses on two essential
32 resources – nitrogen and phosphorus – and challenges their sustainable management in the water-agro-food
33 system of Paris Megacity. An in-depth analysis of the nitrogen and phosphorus imprint of Paris Megacity was

34 conducted, originally centered on human metabolism through consumption and excretion of these two elements.
35 Upstream, the whole agricultural production that feeds Paris Megacity was scrutinized and nitrogen and
36 phosphorus flows in the agro-system were fully documented. Downstream, the analysis of solid waste and
37 wastewater management in Paris Megacity showed the fate of nitrogen and phosphorus imported into the city.
38 Paris Megacity appears to rely on a very complex and international agro-food system, requiring high levels of
39 chemical fertilizers and strongly impacting the environment through nutrient environmental losses. On the other
40 hand, solid waste and wastewater management appears to be mostly disconnected from the agro-food system:
41 even if the release of nitrogen and phosphorus into the environment has largely decreased in recent years, their
42 recycling rate remains very low. This overview of the water-agro-food system of Paris Megacity suggests that an
43 optimal management of nitrogen and phosphorus in the three subsystems (agriculture, waste management and
44 sanitation) should be integrated within a comprehensive approach linking agriculture and urban residues. This
45 analysis thus constitutes a groundwork on which paradigm shift scenarios of the global water-agro-food system
46 could be constructed.

47

48 **Graphical Abstract**

49

50 **Highlights**

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

56

57 1. Introduction

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

68 More than other cities, megacities are characterized by their huge need for material and energy (Kennedy et al.,
69 2015), among which food and water are of utmost importance for the life of their inhabitants. Megacities are not
70 just bigger than most cities: their large and diverse populations, their spatial extension, the amount and diversity
71 of activities that characterize them, the complexity of their functioning make the organization of megacities'
72 metabolism particularly delicate, especially regarding food and water from the point of view of both supply and
73 discharge through waste and wastewater. These have a strong impact on biogeochemical cycles. The
74 characterization of this impact is a key to understanding megacities' metabolism and to considering change in
75 water and food management. This makes it necessary to (i) identify the main biogeochemical flows in terms of
76 socioecological relevance and to analyze the biogeochemical processes involved, (ii) quantify these flows and (iii)
77 locate them at the different stages of their circulation.

78 Nitrogen (N) and phosphorus (P) can be considered as the most critical biogeochemical flows regarding their
79 socioecological impact. Steffen et al. (2015) put forward nine main control variables of the Earth system and
80 suggested planetary boundaries under which these control variables should stay to prevent major shifts in the
81 regulation of the Earth system's stability. Along with biosphere integrity, N and P flows are considered to be in the
82 highest risk zone, ahead of the climate change control variable. The concern about disruption of N and P cycles
83 has been broadly studied and documented. It is of particular significance in Europe where the N cycle intensity is
84 about five times greater than the biospheric cycle, leading to substantial negative damage, from aquatic and
85 terrestrial eutrophication to poor air quality and climate change (Sutton et al., 2011). The environmental dispersion
86 of P is also a matter of concern regarding fertilizer and therefore food production (Cordell, 2010). Phosphate rock
87 has recently been added to the list of critical raw materials by the European Commission (European Commission,
88 2014).

89 Megacities play a major role in N and P flows and depend on them. Urban dwellers' metabolism is embedded in a
90 complex worldwide water-agro-food system resulting in an equally complex biogeochemical imprint. Some studies
91 have provided an overview of urban metabolism through substance flow analysis regarding N or P (Svirejeva-
92 Hopkins et al., 2011; Færge et al., 2001; Forkes, 2007; Barles, 2007) or considered the impact of urban waste
93 and/or wastewater on the environment (Morée et al., 2013). Others have focused on the urban food-print and
94 show the relevance of a spatialized approach (Billen et al., 2009, 2012a, 2012b, 2012c; Chatzimpiros and Barles,
95 2013). However, it seems important to entertain a broader view and to explore both the downstream and the
96 upstream imprint of urban metabolism, as demonstrated by Schmid-Neset et al. (2008) for P. This approach
97 contributes to characterizing the current socioecological regime (Fischer-Kowalski and Haberl, 2007) of
98 megacities.

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

109

110 **2. Material and methods**

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

113 **2.1 Spatial and temporal frame**

114 **2.1.1 Spatial frame**

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

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

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

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

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

133

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

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

136

137

138 **Figure 1.**

139

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

147

148 As stated, the imprint of Paris Megacity largely exceeds its boundaries and each of the three subsystems studied
149 covers a specific imprint zone that can sometimes overlap. Paris Megacity lies within the Seine River basin. It is
150 located 220 km upstream from the estuary where the Seine River flows into the *Baie de Seine* (Seine Bay), as
151 well as into the contiguous North-West Channel and Southern Bight of the North Sea, and is responsible for the
152 development of harmful algal blooms causing severe damage to fish and shellfish populations (Lancelot et al,
153 2007; Passy et al., 2013, 2016). The Seine River basin has therefore been classified as a sensitive area subject
154 to eutrophication in the sense of the 1991 Urban Waste Water Treatment (UWWT) Directive (European Council
155 Directive 91/271/EEC). The 2015 Seine River basin management plan aims at reaching good ecological potential
156 for 2021, as required by the European Water Framework Directive (WFD) (2000/60/CE), including reduction of N
157 and P concentrations. Moreover, the 1992 Oslo-Paris convention required the Seine River basin to halve its N
158 and P flows to the sea between 1985 and 1995. The target on P has been reached, but the flows of N show an
159 opposite trend of +1% per year over the last 30 years (AESN, 2013).

160

161 **2.1.2 Temporal frame**

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

171

172 **2.2 The agro-food system that feeds Paris Megacity**

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

178

179 **2.2.1 Apparent food consumption (availability)**

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

185 Owing to a detailed compilation of the N and P content of each item from the INSEE nomenclature based on
186 information from the CIQUAL and USDA databases on food composition (<https://pro.anses.fr/tableciqual/>;
187 <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
188 (tP/y).

189

190 **2.2.2 Agricultural trade**

191 The trade exchanges of agricultural products between French departments (NUTS3 in the European Union
192 geocode standard, the administrative district between the municipality and the region) were obtained from the
193 French database SitraM (Système d'Information sur le Transport des Marchandises;
194 <http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/>). It annually identifies the transport of
195 50 categories of agricultural products between French departments by roads, railways and navigable waterways,
196 as well as exchanges with foreign countries (customs database). Automated software has been developed by
197 Silvestre et al. (2015) for the analysis of these data. Le Noë et al. (2016) used it to establish a complete matrix of
198 the flows of agricultural commodities exchanged between 33 French agricultural areas (defined by groupings of
199 departments based on the similarity of their agricultural system; see Figure 3) as well as foreign countries
200 grouped into 12 macroregions (Lassaletta et al., 2014). From these data, the relative contribution of each of these
201 47 agricultural regions to the total Ile-de-France food supply was calculated, separately for vegetal and animal
202 proteins. We assumed that there was no significant typological difference between Paris Megacity's food supply
203 and Ile-de-France's food supply; therefore, the food supply of Paris Megacity was deduced by simple application
204 of population ratios.

205

206 **2.2.3 Agricultural production and environmental losses of supplying territories**

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

213 The GRAFS approach is based on a detailed budget of N and P flows including production, transformation and
214 consumption of animal and vegetal products, inputs of N and P fertilizers, atmospheric N and P deposition,
215 symbiotic N₂ fixation, P embedded in feed additives, leaching and erosion in each agricultural region.

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

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

230

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

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

239

240 **2.2.4 Evaluation of Ile-de-France's environmental imprint over its supply areas**

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

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

253
254 In some cases, animal husbandry is based on imported feed such as soybean or oil seed cakes. As a
255 consequence, N and P imports embedded in animal feed need to be accounted for in Ile-de-France's
256 environmental imprint. This is particularly true for regions depending on massive import of animal feed from South
257 America (Brazil, Paraguay, Uruguay, Argentina and Bolivia). Accordingly, the environmental imprint of South
258 America vegetal production has been calculated and the share of this production imported to the regions of
259 intensive livestock farming supplying Ile-de-France has been included in the environmental imprint of Ile-de-
260 France.

261 262 **2.3 Solid food waste generation and management**

263 ***2.3.1 Food waste generation***

264 Food waste appears at all stages of the food supply chain: transformation, transport and storage, distribution and
265 consumption. By far the largest amount concerns the transformation of animal products, particularly slaughtering
266 and cutting activities. Taking into account the cutting balance available for each type of livestock (Benhalima et
267 al., 2015), as well as the N and P composition of each fraction (CIQUAL; USDA; Mello et al., 1978; Ternouth,
268 1990; Little, 1984), waste generation (as blood, viscera, grease, bones, etc.) associated with edible meat
269 production can be evaluated.

270
271 Food waste generated at the latest stages of the supply chain can be evaluated by direct comparison of the
272 above-mentioned data on food availability provided by INSEE, with the data on actual food consumption given by
273 a national detailed inquiry organized in 2006–2007 by the Agence Nationale de Sécurité Sanitaire de
274 l'Alimentation de l'Environnement et du Travail (www.anses.fr/), which provides detailed information on the actual

275 ingestion of food commodities (AFSSA, 2009). Using again the N and P content given by the CIQUAL and USDA
276 databases on food composition, the direct comparison of food availability and food ingestion has been made
277 possible, and losses of N and P at the latest stages of the supply chain have been evaluated by subtraction.

278

279 **2.3.2 Food waste management**

280 N and P flows of food waste management were evaluated by compiling data related to food waste collection and
281 treatment. National data on food waste production and collection are provided by surveys conducted by the
282 French Environment & Energy Management Agency (ADEME, www.ademe.fr): a 2007 campaign characterizing
283 domestic and economic refuse (ADEME et al., 2010) and a 2008 survey of food waste management at the
284 household level (ADEME, 2008). The former study estimates that 75% of the collected food waste comes from
285 households. The latter study is only semiquantitative so several hypotheses regarding actual flows of food waste
286 being managed on-site had to be considered. A proportion of 10% of household food waste was assumed to be
287 managed on-site in Paris Megacity. The obligation of biowaste source separation by the largest producers is very
288 recent and the circular that specifies these obligations dates from 2012 (Circulaire du 10 janvier 2012 relative aux
289 modalités d'application de l'obligation de tri à la source des biodéchets par les gros producteurs (article L 541-21-
290 1 du code de l'environnement) NOR : DEVP1131009C). Given the temporal frame used herein, we consider that
291 only two biowaste source separations are implemented by the largest producers: oil separation in which N and P
292 contents are considered negligible, and bone collection from slaughterhouses and butchers. For the latter, we
293 considered that 5–10% of bones were not collected. Although some bone collection and animal processing takes
294 place inside the city, mostly within butchers, we have considered slaughterhouses and butchers as a whole and
295 excluded them from the perimeter of urban economic activities. Management of biowaste by economic activities
296 and the Rungis International Market were evaluated by a local survey conducted by the French Ministry in charge
297 of food and agriculture (DRIAAF, 2012).

298 Food waste treatment data were collected locally. The Ile-de-France Region Waste Management Observatory
299 (ORDIF, www.ordif.com) has produced a survey of waste treatment facilities in the Ile-de-France region (ORDIF,
300 2014) that distinguishes waste treatment for Paris Megacity and waste treatment of the other Ile-de-France
301 municipalities. Paris Megacity has one major waste treatment authority: the Joint Central Household Waste
302 Treatment Authority for the Agglomeration of Paris (Syctom, <http://www.syctom-paris.fr>). It covers the densest
303 zones of Paris Megacity and serves 54% of the population of Paris Megacity (Figure 2). Syctom is in charge of the
304 treatment of waste and does not receive any separate collection of food waste. All food waste treated by the
305 Syctom currently goes into three incineration plants located close to the Paris city center in Ivry-sur-Seine, Issy-
306 les-Moulineaux and Saint-Ouen. There are 14 other incineration plants that receive the waste of Paris Megacity.
307 Data on waste composition and waste treatment from the Syctom were analyzed in their annual activity reports
308 and exploitation data (Syctom data, personal communication) and extrapolated to Paris Megacity.

309

310 **2.4 Wastewater management in Paris Megacity**

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

314

315 **2.4.1 Flows of N and P outside wastewater collection**

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

317 (i) human by-products of metabolism that are not in the form of urine and feces. These by-products can take three
318 forms: integumentary and accidental losses (sweat, hair, menstruation, bleeding, etc.), breathing and N and P
319 stocked in the body. Sutton et al. (2000) estimated that N volatilization related to sweat excretion accounts for 14
320 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.
321 Taking into account that many integumentary losses reach the sewers through showering or clothes washing, a
322 general value of 0.5% metabolized N and P not reaching the sewers was taken into account for breathing and
323 integumentary losses. N stock in the human body is estimated at less than 0.5% of total N ingested during an
324 individual's lifetime. P is mostly stocked in bones and is not negligible. We assume a 1% P content in the human
325 body for a mean weight of 70 kg (INSEE), thus 0.7 kgP total stock in the body.

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

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

333

334 **2.4.2 Flows of N & P in wastewater**

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

343 SIAAP operational data to the whole population of Paris Megacity. We used SIAAP operational data between
344 2004 and 2014 (SIAAP, personal communication). The year 2013 was selected for the results of the treatment
345 plants because it was the first year when routine denitrification in Achères was in full operation. It was also
346 considered representative in terms of rain events and collection efficiency.

347 Discharges from the sewer network were calculated as the sum of dry weather discharges and rain weather
348 discharges as combined sewer overflows. These data were evaluated from the sanitation master plan of the
349 SIAAP area approved in 2017 (SIAAP, personal communication). N & P discharges to the sewer network
350 unrelated to human metabolism were calculated by the difference between metabolic inputs, sewer discharges
351 and treatment plant inputs. Food waste inflows were estimated on the basis of grey water composition (Deshayes,
352 2015; Larsen et al., 2013, chap. 17; Chaillou et al., 2011). N and P discharge in rivers and N and P content in
353 sewage sludge were calculated on the basis of SIAAP data. N₂ emissions were deduced by subtraction and N₂O
354 emissions were calculated from measurements taken at the Achères wastewater treatment plant (Bollon et al.,
355 2016a and 2016b) and extrapolated to Paris Megacity. SIAAP sludges are either incinerated or recycled in
356 agriculture through direct spreading or composting. Sludge spreading plans were examined to quantify and
357 localize N and P recycling on agricultural lands.

358

359 **Figure 2.**

360

361 **3. Results**

362 **3.1. The agro-food system supplying Paris Megacity**

363 **3.1.1. Food supplying areas**

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

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

371 The animal protein supply is much more dispersed: 19 French regions contribute more than 1% each and
372 together supply 55% of Paris Megacity animal proteins. Three of these regions – Bretagne, Loire Aval and
373 Manche – account for 32% of the Paris Megacity animal protein supply. They are strongly specialized in intensive
374 livestock production, which depends on massive imports of animal feed from South America (Le Noë et al., 2016,
375 2017). As those regions are spatially distributed in western France (Figure 3), the whole area is hereafter called
376 the “Great West” and is classified as an “intensive livestock farming” region. On the other hand, the 16 remaining
377 regions total 23% of the animal protein supply. They are much less specialized in one or another type of
378 production, but they occupy a larger agricultural area; in addition, the proportion of permanent grassland is largely
379 equivalent to that of arable land. These features characterize these regions as “mixed crop and livestock farming.”
380 We call the “Great East” a territory formed by six regions (Loire Amont, Grande Lorraine, Cantal-Corrèze, Ain-
381 Rhône, Isère-Drôme-Ardèche and Bourgogne), which supply 13% of Paris Megacity animal proteins.
382 Furthermore, various foreign countries contribute to the animal food supply (Figure 3). Their local environmental
383 imprint is not directly calculated because of the lack of information regarding the functioning of the agro-food
384 system and the uncertainties regarding their N and P environmental losses. Yet based on literature data (Billen et
385 al., 2014) we have classified foreign countries as being close to the intensive livestock farming or mixed crop and
386 livestock farming typologies. This allows us to estimate the share of animal proteins provided by intensive
387 livestock farming regions or mixed crop and livestock farming regions (Figure 5).

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

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

396 **Figure 3.**

397

398 ***3.1.2 The agro-food system of the supplying territories***

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

410 **Figure 4.**

411

412 ***3.1.3 Environmental imprint of Paris Megacity food supply***

413 As stated above, the imprint of Paris Megacity food consumption in each supplying area is defined as the
414 resources consumed and the environmental nutrient losses, which are attributable to the food supply of Paris
415 Megacity. Table 2 summarizes the calculated imprints over the four main supplying areas which contribute 62% of
416 the total protein supply of Paris Megacity. Overall, this agricultural area is estimated at about 2.5 million ha of
417 which approximately one-third are grassland areas, almost all located in the mixed crop and livestock farming
418 area. When these absolute numbers are reduced to the population of Paris Megacity, it appears that 0.26 ha is
419 required for this part of the food supply per inhabitant (62%). Of these, only 0.011 ha, less than 5%, is dedicated
420 to the supply of vegetal proteins, the remaining being mostly devoted to meat and milk production. The total
421 nitrogen imprint of these agricultural activities across these areas is estimated to be a surplus of 114 ktN/y with

422 about one-fourth of this surplus in grassland and a NH₃ volatilization of 38 ktN/y. Yet it is necessary to take into
 423 account that environmental consequences of the N surplus on arable land and on grasslands are significantly
 424 different. On arable land, about 70% of the N surplus ends up in the hydrosystem (Billen et al., 2013). In contrast,
 425 N inputs contributing to the N surplus in grassland, below a threshold of 100 kgN/ha/y, keep accumulating in the
 426 soil organic matter pool (Billen et al., 2013). Accordingly, the surplus observed in grassland should not necessarily
 427 be viewed as a negative environmental impact, as it accompanies the increase of the soil organic matter pool.
 428 The P eroded from those areas feeding Paris Megacity is estimated to reach 3.2 ktP/y with 95% derived from
 429 arable land. However, it is difficult to determine the amount of P reaching the surface water because eroded
 430 particles can accumulate in downhill and riparian sectors.

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

438

439 **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	<i>Cropland</i>	109 206	384 098	271 940	652 620	1 417 863
	<i>Grassland</i>	-	116 778	-	840 686	957 464
N fertilizers, ktN/y	<i>Cropland</i>	16	17	16	36	85
	<i>Grassland</i>	0.1	3.8	-	25	29
Feed import, ktN/y	<i>Livestock</i>	-	36	-	4.2	40
NH₃ emission, ktN/y	<i>Livestock</i>	-	14	-	24	38
N surplus, ktN/y	<i>Cropland</i>	4.7	26	18	26	74
	<i>Grassland</i>	0.5	2.8	-	30	33
P fertilizers, ktP/y	<i>Cropland</i>	1.5	1.9	7.8	3.7	11
	<i>Grassland</i>	0.5	0.1	-	2.9	3.5
Soil P accumulation (or depletion), ktP/y	<i>Cropland</i>	-1.2	5.1	0.7	1.7	6.3
	<i>Grassland</i>	-	0.1	-	1.9	2
Feed import, ktP/y	<i>Livestock</i>	-	5.6	-	1.4	7.0
Feed additives, ktP/y	<i>Livestock</i>	-	5.7	-	7.1	12.8
P erosion, ktP/y	<i>Cropland</i>	0.5	1.1	No value	1.4	3.0
	<i>Grassland</i>	-	0.03		0.2	0.23

440

441 *All French mixed crop and livestock farming regions contributing more than 1% of the animal food supply of Paris Megacity.
442

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

445 **Figure 5.**

446

447 **3.2 Food waste flows in Paris Megacity**

448 **3.2.1. Waste generation in the food transformation industry**

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

451 The transformation of living animals into edible products generates a huge amount of waste evaluated at 1.1 kgN
452 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
453 related to the high P content of bones. This represents a per capita production of slaughtering and cutting wastes
454 for Paris Megacity of 3.9 kgN/cap/y and 0.8 kgP/cap/y, respectively.

455

456 **3.2.2. Food waste at the retail and consumer level**

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

464

465

466

467

468

469

470

471

472 **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

473

474 **3.2.3 Food waste management**

475 The N and P food waste flows in Paris Megacity are illustrated in Figure 6a and b. Apart from bone collection and
476 other recovery of animal waste, the main form of reuse is represented as on-site food waste disposal by

477 households. According to ADEME (2008), this on-site disposal mainly takes the form of animal feeding (pets and
478 wild animals). Since excretions of urban animals are seldom recovered, animal feeding ultimately adds to the

479 environmental losses of N and P in the city. Composting food waste is a minor form of on-site reuse. It is of

480 course more common in the parts with the lowest population density. Only about 100 collective composters were

481 counted in the Paris city center in 2012 (www.paris.fr, compost section). We can therefore assume that less than

482 1% of household food waste is composted in Paris Megacity's densest areas. However, when food waste is

483 composted, it is used for garden food production in two cases out of three, which therefore contributes to effective

484 N and P recycling. Food production inside Paris Megacity is nevertheless considered negligible.

485 In the end, more than 80% of food waste is collected by municipalities together with other residual waste.

486 Whereas green waste from the garden is often collected separately, only one waste treatment plant, located in

487 Saint-Ouen-l'Aumône, receives source separated food waste and composts it in Paris Megacity (ORDIF, 2014).

488 Three other waste treatment plants in Paris Megacity carry out mechanical-biological sorting of residual waste for

489 composting or methanization. However, they receive less than 1% of the total Paris Megacity food waste

490 production.

491 In Figure 6a and b, economic activities represent all places where food waste is handled out of the households:

492 markets, supermarkets, restaurants, canteens, bakeries, etc. (except for activities leading to bone collection as

493 specified in section 2.3.2). The Rungis International Market, reportedly the largest market of agricultural products

494 in the world, performs food waste composting or methanization, but this accounts for less than 1% of Paris

495 Megacity food waste production. Except for collection of bones within butchers, other economic activities mostly

496 rely on mixed residual waste collection for food waste disposal.

497 Finally, incineration is the prevailing destination of Paris Megacity food waste. It entails negligible releases of

498 reactive N and P in the environment, but it does not achieve any form of N & P reuse. N content in food waste

499 turns back into the atmosphere as N_2 . P stays in the bottom ash and is stabilized in clinker. Clinker is mostly used
500 as construction material, which does not allow specific P reuse.

501

502 **Figure 6.**

503

504 **3.3 Wastewater flows in Paris Megacity**

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

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

519 The proportion of P collected in the sewers that is not related to excretion or food waste is much higher than for N,
520 mainly because of the use of P in detergents. It accounts for 30% of the total collected phosphorus in 2013, i.e.,
521 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
522 of P in detergents. It is expected to continue decreasing with a new limitation on P in dishwashers that will come
523 into effect in 2017 by application of EU regulation No. 259/2012 of the European Parliament and of the Council of
524 14 March 2012. Total P discharge in the rivers represents 18% of total P entering the networks, but only half of
525 the sludge is directly spread on agricultural land or composted. The other half is incinerated in various facilities
526 and P is not recovered from incineration ashes.

527 N is mostly emitted from wastewater treatment plants in the form of gas, predominantly N_2 , but also in small
528 proportions in the form of N_2O . Kampschreur et al. (2009) reported a considerable range of uncertainty regarding
529 N_2O emissions in wastewater treatment plants, varying from 0.05% to 25% of N-load. Recent measurements at
530 Achères wastewater treatment plant lead to a 2% ratio. N recycling to agriculture is negligible. Total N discharge
531 in the river from the area's wastewater treatment plants respects the UWWT Directive regulatory threshold of
532 30%, but the effective global rate of N river discharge from the wastewater system is about 38%. For a megacity

533 like Paris, this means that the metabolic N of about 4 million people is discharged daily into the Seine River in a
534 reactive form (mostly NO_3^-).

535

536 **Figure 7.**

537

538 **3.4 Overview of the nitrogen and phosphorus imprint of human metabolism in Paris Megacity**

539 The results on the biogeochemical imprint of human metabolism in Paris Megacity from all three subsystems of
540 agro-food production, waste management and wastewater management are compiled and summarized in Figure
541 8a and b. The imprint for other agricultural regions than the four supply areas studied was deduced by
542 extrapolation, considering the same characteristics for these regions as for their corresponding studied
543 counterpart. N and P loads to the wastewater management that are not directly related to food and excretion were
544 also removed and subsequent flows proportionally recalculated. They allow a general vision of this imprint that
545 contributes to characterizing a socioecological regime (Fischer-Kowalski and Haberl, 2007) as discussed in
546 section 4.2.

547

548 **Figure 8.**

549

550 4. Discussion

551 4.1 Quality of results and uncertainties

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

558
559 The uncertainties concerning the GRAFS flows are extensively discussed in Le Noë et al., 2017. In the present
560 study, the P imprint of Paris Megacity has been calculated on the basis of the N imprint by using of N/P ratios. It
561 leads to a slightly unbalanced P budget showing a 21% to 38% gap between inputs and outputs on figure 5 and
562 figure 8.

563 Regarding our N & P flow calculations in the waste management subsystems, their reliability is difficult to
564 establish. Most data on food waste are given in kilograms of food waste, but our approach is based on N and P to
565 trace the actual nutrients contained in food necessary for human metabolism. Figures in kilograms of food waste
566 are difficult to interpret given the variability of the moisture in food waste (some of the collected studies take
567 liquids into accounts and others exclude them). Moreover, it is difficult to accurately analyze the composition of a
568 trash bin and its specific content in food waste (ADEME et al., 2010; Sycotom data). All types of waste are usually
569 mixed in residual waste bins and it is difficult to sort them again. However, Sycotom data enable the calculation of
570 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
571 we consider that most N and P comes from food waste, these values tend to show a correct estimation for N and
572 P collected in waste bins. Data on P could not be cross-checked with local analysis of bottom ash since this
573 element is not measured on Sycotom ash. Calculated values of N and P losses between the slaughter/cutting and
574 packaging steps are taken into account in the GRAFS representation, but the fate of these flows remains
575 uncertain. Yet a complete analysis of P recovery and recycling from waste is provided by Senthilkumar et al.
576 (2014). This study was conducted at the national scale, so it is difficult to convert it to local food waste
577 management considerations.

578 Application of the literature values on P content in bottom ash in France (Aouad et al., 2006) gives a total
579 production of 0.24 kgP/cap/y for Paris Megacity, as compared to 0.31 kgP/cap/y in our calculations. N can
580 unfortunately not be measured after combustion since it eventually goes back to the atmosphere as N₂.

581

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

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

593 Interannual variability of quantities of N per capita received by the SIAAP in recent years is quite low ($\pm 5\%$) and
594 2013 is in the middle of this variability range. The decrease of P values is known to stem from the limitation of P
595 use in detergent and confirms the validity of the measured values.

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

600

601 **4.2 The main characteristics of the water-agro-food socioecological regime of Paris Megacity**

602 **4.2.1 A minimized local imprint on Paris Megacity area**

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

612 The wastewater authorities of Paris Megacity are currently undertaking or scheduling complementary intensive
613 pollution mitigation works. The Seine in the Paris city center only has a monthly minimum flow with a 5-year return
614 period of $94 \text{ m}^3/\text{s}$ (DRIEE-IF, 2014), which leaves only 830 L/cap/day of dilution capacity. The WFD threshold of
615 $0.5 \text{ mgNH}_4^+/\text{L}$ in the Seine River thus requires at least 98% efficiency in reduced N removal. Despite reaching the

616 limits of the technical feasibility of centralized wastewater treatment, ammonium concentrations in the river should
617 be lowered in the coming years to values compatible with the WFD. On the other hand, nitrite concentrations
618 remain an issue. Even with advanced wastewater treatment, the compatibility of the centralized environmental
619 impact of treated water discharge with the preservation of the local environment remains an issue in a megacity.
620 The expected decrease of the Seine River flow in the coming years due to climate change will challenge this
621 paradigm even more.

622 Moreover, two main forms of N release have an imprint at a larger scale than Paris Megacity area: more than
623 $20 \cdot 10^6$ kgN annual export of N to the estuary, mainly in the form of nitrates, and about 400 ktCO₂eq annual N₂O
624 emissions from the wastewater treatment plants.

625

626 **4.2.2 Poor reuse of nitrogen and intermediate reuse of phosphorus**

627 Urban reuse of N and P flows is assessed by their recovery rates. The N cycle is the most extreme in terms of
628 linear management since only 3% of the N entering the city (7.3 kgN/cap/y) goes back to the agro-food system
629 (0.2 kgN/cap/y), whereas the agricultural production system requires about 570% of the N (37.4 kgN/cap/y) that is
630 eventually supplied as food (6.6 kgN/cap/y). The fate of P is more contrasted. First, bone collection and other
631 agro-industrial waste reuse enable recycling 75% of P (Senthilkumar et al., 2014). Second, the overall recycling
632 rate of the wastewater system is only 41% and urban food waste recycling is negligible. Thus 70% of the P of
633 urban food (0.79 kgP/cap/y) ends up unrecovered in clinker (0.48 kgP/cap/y) or water discharges
634 (0.08 kgP/cap/y).

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

640 The geographic spread of food supply and urban residue reuse appears dissymmetrical. There is a political
641 commitment not to exceed 200 km for the spreading of sewage sludge (cf. Public Debate on Achères wastewater
642 treatment plant in 2007, e.g., Question & Answer No. 80: <http://cpdp.debatpublic.fr/cpdp->

643 [seineaval/participer/reponses-questionsdcfd.html?id=4](http://cpdp.debatpublic.fr/cpdp-seineaval/participer/reponses-questionsdcfd.html?id=4)), whereas the agro-food system of Paris Megacity is
644 based on $2.7 \cdot 10^5$ ha of soybean cultivation in South America and $5 \cdot 10^5$ ha of intensive livestock farming in the
645 Great West, mostly located more than 300 km from the Paris city center.

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

650
651 Our regionalized approach also makes it possible to calculate the amount of N and P that is recycled through
652 sewage sludge spreading or composting on agricultural lands that supply food to Paris Megacity (an effective
653 nutrient recycling loop). This figure is totally negligible for N, given the low amount of N in sewage sludges. For P,
654 the figure also remains very low and we estimate that 0.03% of the total vegetal P ingested by the inhabitants of
655 Paris Megacity comes from effective recycling of excreted P. Around 80% of the recycled sludges are effectively
656 spread on the Paris Central Basin that supplies Paris Megacity with vegetal food, but this region is largely
657 dedicated to the export of cereals, so the recycled P of Paris Megacity is mostly exported. Assuming that three-
658 quarters of the daily ingestion of 100 g of bread per person per day (AFSSA, 2009) is in the form of the
659 “baguette”, we can still estimate that, on average, the P of 1,000 daily “baguettes” ingested by the inhabitants of
660 Paris Megacity, out of more than 3 million, comes from direct recycling of the P contained in their urine and feces.

661
662 **4.2.3 The externalized imprint of Paris Megacity**
663 With the environmental imprint of Paris Megacity becoming less and less significant on the urban area itself, Paris
664 Megacity has nearly completely externalized the environmental imprint of human metabolism on agricultural
665 lands. It makes it largely invisible for urban dwellers, seldom conscious that pollution in South America or in the
666 Great West is directly related to their consumption of food.

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

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

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

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

691

692 ***4.2.4 The central issue of human metabolism***

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

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

706

707 **4.3 Changes in the imprint of human metabolism in Paris Megacity**

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

711

712 ***4.3.1 Possible optimization paths***

713 According to our analysis, agriculture, through resource consumption and nutrient release to the hydrosphere and
714 the atmosphere, produces by far the largest imprint of urban metabolism, compared to waste and wastewater
715 management. Yet since the late 1980s considerable effort has been expended to optimize agricultural practices

716 and fertilizer use in the scope of what is called “reasoned agriculture”. This effort has succeeded in stabilizing
717 agricultural N pollution to a level that is, however, still incompatible with good ecological status of most water
718 bodies (Passy et al., 2016; Romero et al., 2016), not only because of the slow response of long residence time
719 soil and aquifers nutrient pools, but also because of the unavoidable losses generated by intensive and
720 specialized chemical agriculture (Billen et al., 2016). It is clear, therefore, that deep structural changes of the agro-
721 food system, beyond the mere optimization of agricultural practices, will be necessary to further reduce the
722 environmental imprint of Paris Megacity food supply. One of the most striking characteristics of the current
723 agricultural system supplying Paris Megacity is its spatial specialization into either crop farming or livestock
724 farming areas, with very few connections between them (Le Noë et al., 2016). Inverting this specialization trend
725 and reconnecting crop and livestock farming is likely to be the best option for reducing agricultural nutrient
726 pollution (Lemaire et al., 2014; Bonaudo et al., 2014; Garnier et al., 2016; Billen et al., 2016). Exploring scenarios,
727 several studies at the regional and global scale have demonstrated that a reduction in animal protein in the diet,
728 while reconnecting crop and livestock production, would clearly reduce ground and surface water nitrate
729 contamination, major changes that are compatible with organic farming (Billen et al., 2015; Garnier et al., 2016;
730 Lassaletta et al., 2016).

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

740

741 Food waste management should be substantially optimized in the coming years. Two recent laws address
742 biowaste management in France: (i) the above-mentioned legislation on large biowaste producers (section 2.3.2).
743 Since the beginning of 2016, all producers of more than 10 tons on biowaste per year (e.g., a canteen serving 300
744 people per day) are required to specifically reuse their biowaste. (ii) The law on energetic transition (“Loi n° 2015-
745 992 du 17 août 2015 relative à la transition énergétique pour la croissance verte”). This law requires that waste
746 management public services should enable all citizens to reuse their biowaste by 2025 (Art. 70. V. I.4°). In this
747 perspective, experimental collection of biowaste has started in 2017 for 157,000 inhabitants of the Paris city
748 center. Unfortunately, these laws are mainly carbon-oriented and do not point to N and P recovery as an
749 important issue. The future trajectory of food waste N and P in Paris Megacity will then depend not only on the

750 effective application of these laws, but also on the actual implication on N and P in the general concept of
751 “biowaste reuse.”

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

768

769 **4.3.2 The limits to minimizing the imprint of Paris Megacity**

770 This study shows that there is considerable room for improvement in minimizing the biogeochemical imprint of
771 Paris megacity. Nevertheless, it has to be kept in mind that our approach based on N and P flows is necessarily
772 limited in its findings. Describing the water-agro-food system of Paris Megacity solely through N and P flows
773 leaves aside many other aspects of this system: water consumption, greenhouse gas emissions, energy
774 requirements, sanitary issues, etc. Moreover, accounting for flows in terms of N and P does not take into
775 consideration the specific form in which N and P are embedded and the constraints related to the management of
776 these flows (fertilizers, manure, food, food waste, human excreta, etc.). Nonetheless, given the importance of the
777 stake of proper management of N and P, in terms of both resource management and environmental disruptions,
778 the low efficiency of water-agro-food system of Paris Megacity remains striking. Urban and agricultural N and P
779 management appears mostly disconnected, which reflects disconnected sectorial policies of food production,
780 waste and wastewater management. Efficient N and P management of the water-agro-food system of Paris
781 Megacity appears to be a neglected part of the equation and this study highlights this point. As stated by
782 Rosemarin (2010) for P and Sutton et al. (2011) for N, the importance of correct management of N and P flows is

783 currently an outcome of the research led by the scientific community, but awareness and transposition into
784 policies is not yet fully effective, although several improvements are on-going, as stated in section 4.3.1. An
785 integrative analysis appears useful for supporting decision-making and integrating social, health and economic
786 issues into the urban-rural metabolism framework (Kennedy et al., 2011).

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

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

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

803

804 **5. Conclusion**

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

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

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

827

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