



Full length article

A N, P, C, and water flows metabolism study in a peri-urban territory in France: The case-study of the Saclay plateau

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ABSTRACT

Facing environmental issues, such as excess of nitrogen in the biosphere, water eutrophication, carbon emission in the atmosphere or hydrological impacts, peri-urban areas are not receiving as much attention as urban areas. In this research, we focus on a French peri-urban area in the Parisian region, the Saclay plateau. Following the territorial ecology approach, we consider this territory as a system organizing agricultural, food and waste flows, and we have analyzed the metabolism of this territory through its N, C, P and water flows. The results show first that the metabolism of the Saclay plateau is largely open, i.e. the main flows are input and output flows, and internal flows are small or nonexistent. This is particularly the case for nitrogen and phosphorus flows. The same findings hold for carbon flows although primary production and respiration play the major role in the carbon metabolism. Besides the uncertainty of the available data, water flows also reveal a clear uncoupling between compartments of the system. The analysis of these material flow budgets reveals the high potential for reconnections of the different flows, mainly due to the presence of large areas of agricultural land and a large population. Implementation of biowaste recovery, recovery of human excreta at source, as well as rain recovery systems, could help to realize this potential provided that environmental and sanitary risks can be effectively managed. Developing a foresight approach based on scenarios of territorial metabolism can assist in the building process of a territorial project in periurban areas.

1. Introduction

The metabolism of a territory refers to the material and energy flows and stocks making possible the human activities in the territory. The characterization of the territorial metabolism facilitates our understanding of society-nature interactions and is strongly connected to sustainability issues such as the local and remote environmental impacts of material and energy consumption. Territory is intended here in its French geographical sense, i.e., a delimited area organized and appropriated by humans: it can be an administrative area, or any area that has social meaning in terms of appropriation, management, development, perception or representation (Elissalde, 2002).

The study of territorial metabolism has gained importance over the past fifteen years through material and/or substance flow analysis (MFA and/or

SFA).¹ These analyses are mainly applied at the regional (Marteleira et al., 2014), national (Schiller et al., 2017; Zeng et al., 2017), and global level (Schipper et al., 2018), or to specific areas and activities such as industrial parks (Martín Gómez et al., 2017). Cities have also been investigated, usually from the point of view of urban areas as a whole (Zhang, 2013; Kennedy et al., 2015; Li and Kwan, 2018; Céspedes Restrepo and Morales-Pinzón, 2018), although some studies address the differentiation of the metabolism within the urban area (Rosado et al., 2014). These works are part of industrial ecology (Ayres and Ayres, 2002; Fan et al., 2017), social ecology (Haberl et al., 2016), and, more recently, territorial ecology, a field of research developed in France. Territorial ecology aims at characterizing the social metabolism on a local basis, in order to better understand the ways in which society and nature interact. It also argues that, in addition to quantifying material and energy flows and stocks, the natural and social

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¹ As evidenced, for instance, by the growing number of papers published on those topics in the *Journal of Industrial Ecology*.

drivers of these flows and stocks must be analyzed (Buclet, 2015). In this respect, territorial ecology can be seen both as an interdisciplinary research field and as a decision support tool for local authorities. It can serve to enhance the governance of material flows (Barles, 2010), from the perspective of a circular economy as a sustainable alternative to the linear metabolism that characterizes the present situation (Kalmykova et al., 2017).

This paper analyzes the metabolism of a particular type of territory, namely a peri-urban territory. Peri-urban territories present three distinctive features (Allen, 2003): (i) a specific interface with complex mosaics of juxtaposed activities such as economic activities, urban-oriented leisure activities, semi-natural ecosystems (forests, wetlands), agriculture, road networks, housing, etc.; (ii) an heterogeneity and vulnerability of peri-urban communities with the co-existence of stakeholders who have different and often competing interests, practices and perceptions; and (iii) an institutional fragmentation and overlapping of institutions which constitute a major difficulty in establishing effective governance. Peri-urban territories can be seen as sub-systems of a wider urban system, but they can also be taken as separate objects of study. Several authors have called for the implementation of specific management in such peri-urban areas (Simon, 2008), based for instance on the design of urban-rural bio-geochemical cycling (PURE management, Zhu et al., 2017).

While peri-urban territories are more and more concerned with sustainability issues, they have seldom been studied using territorial ecology tools. Barles (2009) has compared the peri-urban to the urban metabolism in the case of the Paris region, emphasizing the role of construction materials in urban sprawl, and Marty (2013) has examined the relationships between a city and its periphery. Gombert-Courvoisier et al. (2013) have addressed the question of household waste, Wassenar et al. (2017) the recycling issue, and Parkinson and Tayler (2003) the problem of waste water. These studies however provide only partial and uneven knowledge of the peri-urban metabolism. Our paper seeks to fill this gap by focusing on the first feature highlighted by Allen (2003).

To this end, we set out to characterize the metabolism of a peri-urban territory, the Saclay plateau (France), a place where intensive agriculture encounters huge urban pressure. Considering these issues, we focus on the agricultural, food, and solid and liquid waste systems. Tedesco et al. (2017) have proposed a first description of the food system of the Saclay plateau, with a focus on nitrogen flows, and have analyzed the potential for local food self-sufficiency. Our work draws on the method they have developed and extends the bio-geochemical analysis by including phosphorus, carbon and water flows (it furthermore considers processes other than cropping systems, such as forests and green spaces).

These flows are all connected with several important environmental problems. Nitrogen availability limits plant growth and is essential to human and animal diets (Billen et al., 2009), but causes water contamination through excess nitrate leaching or wastewater discharge, as well as atmospheric contamination through N₂O and NH₃ emission (Garnier et al., 2014). Mineral fertilizers used by farmers are produced through energy-costly processes. Phosphorus is also essential to plant growth. This natural resource is absent from the atmosphere and concentrated ores in phosphorus mines are exhaustible. Its availability in highly concentrated natural deposits could be exhausted in less than a century (Cordell et al., 2009). It also contributes to water eutrophication (Carpenter and Bennett, 2011). Carbon is an element of all living systems, and the carbon cycle is of major importance as increasing presence of carbon dioxide and methane in the atmosphere are currently driving climate change (Pellerin et al., 2013). Furthermore, in a peri-urban context, including the Saclay plateau, the hydrological functioning can be affected by waterproofing of lands due to urbanization. This increases streaming and raises the level of flood risk in certain areas. Simultaneously, waterproofing can lead to hydric deficit, due to a decrease of infiltration and a lack of phreatic table restocking.

2. Case study and method

2.1. Case study

The Saclay plateau is located 20 km south-west of Paris (France), in the heart of the green belt of the Île-de-France region, across two *départements*² and three agglomerations of municipalities (Fig. 1). Surrounded by three river valleys, the territory includes 18 municipalities and 175,106 inhabitants on 15,594 ha. These municipalities were chosen as part of the area of intervention of Terre & Cité, a non-profit association whose members include 20 municipalities and which is involved in the preservation of farming and in the conservation of rural and natural areas on the plateau. Terre & Cité helped us during the study and wishes to use these results as a basis for local projects.

Agriculture remains an extensive activity as it occupies 28% of the area – the total agricultural area was 4039 ha in 2013, divided among 20 farms. As depicted in Tedesco et al. (2017), three types of farms can be found: conventional field crop farms compatible with grain production basin dynamics; diversified field crop-based farms taking advantage of the peri-urban situation (production sold through short supply chains, conversion to organic farming, green waste composting, cattle farming); and small specialized farms (poultry farming, tree nursery, beekeeping, social farming, equestrian activity, community gardens) (Fig. 2).

Between 1982 and 2012, 1402 ha of agricultural land were lost, and mainly transformed into built-up areas (source: EVOLUMOS 1982–2012). In 2006 the French State decided to develop the “Paris-Saclay” research-university cluster and centre for entrepreneurship on the plateau, a project of regional and national importance, aimed at improving France’s scientific competitiveness. In reaction to this galloping urbanization, Terre & Cité was created in 2001, and a protection zone called ZPNAF (*Zone de protection naturelle, agricole et forestière*) was set up by law in 2012 to protect the agricultural and natural areas of the plateau, consisting of 2300 ha of agricultural lands.

The combination of highly productive agriculture and huge urban pressure, together with the multilevel and contradictory content of the various policies that are implemented on the Saclay plateau create a situation that is emblematic of periurban territories.

2.2. Method

In order to characterize the metabolism of the Saclay plateau, we focused on agricultural activities and the consumption of agricultural products. Hence, apart from water flows, industry-related flows were not taken into account. The system was divided into 7 compartments for N, P and C flows: arable lands, grasslands, livestock, green spaces, forests, local population, and composting activity. Flows between these compartments are represented following the GRAFS approach (Generic Representation of Agro-Food Systems, Billen et al., 2014). The conversion rates in terms of nitrogen, phosphorus and carbon content are given in Table A1 (Appendix A). As the analysis draws on the method initiated by Tedesco et al. (2017), in this section we discuss only those data that were not taken into account in their paper.

2.2.1. Arable lands and grasslands

Agricultural areas per crop are assessed with the European Land Parcel Identification System (LPIS) database and the RPG Explorer software, by taking the average area from 5 years of production (2010–2014). Estimation of yields comes from Tedesco et al., 2017. Production of arable lands is mainly exported outside the territory, while 12% in terms of nitrogen produced serves as feed for the livestock, and 1% is directly sold for human consumption on the territory (60 tons/year of organic wheat and

² A *département* is a French administrative unit that encompasses several municipalities (NUTS 3 in the European nomenclature).

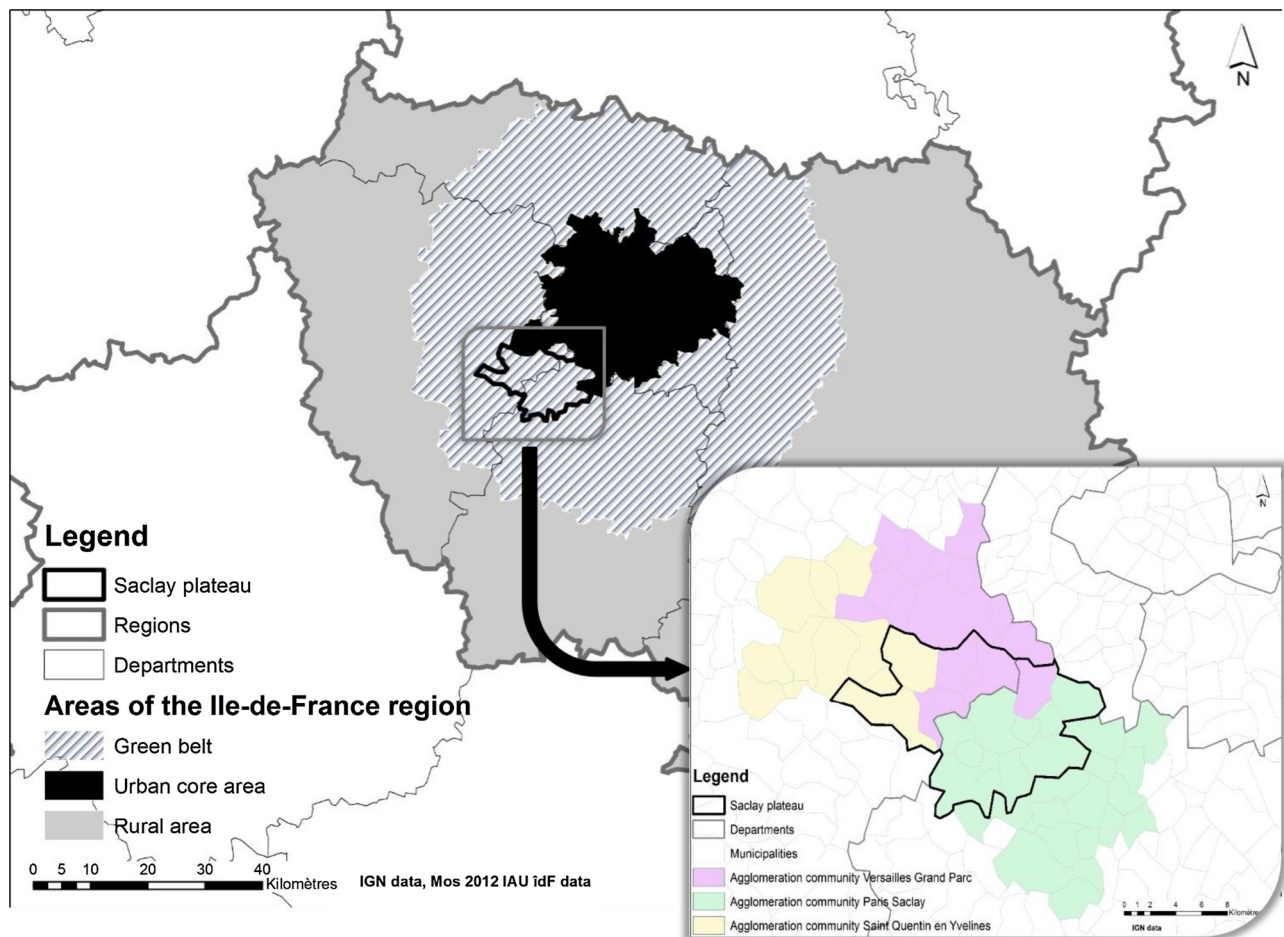


Fig. 1. The Saclay plateau located in the green belt of the Île-de-France region and at the crossroad of several administrative entities. The notion of Green Belt was formalized by the institute for development and planning for Île-de-France. The Green Belt is an area between 10 and 30 km from the gates of Paris where all the wooded, agricultural and natural spaces are preserved and developed.

the whole production of market gardening). Both grasslands and arable lands receive organic fertilization (green waste compost and manure from livestock, Tedesco et al., 2017).

Parameters for the biological process of symbiotic fixation of nitrogen and nitrogen atmospheric deposition are taken from Tedesco et al. (2017), and organic fertilization is known (see below). The total surplus of nitrogen for arable lands and grasslands in the Paris region was estimated at 34 kgN/ha (Bouchaib, 2012). N_2O emission from organic fertilizers was estimated to be 2.9% for grasslands and 1% for arable lands (Peyraud et al., 2012). The emission/volatilization in the form of N_2O and NH_3 of mineral fertilizers is estimated to be 4.3% (SOeS, 2013). Volatilisation of nitrogen due to crop residue in arable lands and grasslands was estimated from De Klein et al., 2006 (Table A2, Appendix A). We assumed that the soil nitrogen stock is constant. From the nitrogen content of production of arable lands and grasslands, the nitrogen supplied by organic fertilizers, atmospheric deposition and symbiotic fixation, as well as the nitrogen surplus, the volatilisation due to crop residue and the volatilisation of organic and mineral fertilizers, we deduced the amount of nitrogen in synthetic fertilizers applied on arable lands and grasslands.

Rate of phosphorus atmospheric deposition is estimated to be 0.4 kgP/ha/year (Le Noë et al., 2017). There is no mineral phosphorus input for grasslands (Ageste, 2010). We therefore estimated the phosphorus accumulation in grassland soils by subtracting the organic phosphorus inputs for grasslands from the production of grasslands. The rate of phosphorus soil stock decrease in arable lands was assumed to be -1.8 kg P/ha/year (Le Noë et al., 2017). The amount of mineral phosphorus spread on the arable lands was therefore approximated by subtracting the organic phosphorus spread on the arable lands and the

atmospheric deposition of phosphorus from the phosphorus imbedded in the production of arable land and the decrease of phosphorus in the soil.

The application of lime on grasslands and arable lands, which causes gaseous emission of carbon ($0.44 \text{ kgCO}_2/\text{kgCa}(\text{CO}_3)$), was estimated at $0.16 \text{ tCa}(\text{CO}_3)/\text{ha}$ (SOeS, 2013). Harvest index, root shoot ratio, and humification coefficient for above and below ground parts of the different crops, as well as humification coefficient for manure, compost and direct grazing extraction were estimated from Le Noë et al. (2017), and are presented in Table A3 (Appendix A). They were used to estimate the production of unharvested crop residues and underground tissues, input of humified organic carbon to soil, as well as the respiration of crop residues. The carbon capture due to net primary production, including exported harvested products, crop residues and underground production was also calculated. Assuming that the carbon stock in the soil was in equilibrium on the short term, the loss of carbon from the soil was considered equal to the carbon inputs (humified organic matter from organic fertilizers and residues). Part of this loss is due to carbon leaching, which was assumed to be $180 \text{ kgC}/\text{ha}/\text{year}$ for arable lands, and $290 \text{ gC}/\text{ha}/\text{year}$ for grasslands (Kindler et al., 2011), the rest represents soil respiration.

The estimated carbon stock of the soil for grasslands is $85.5 \text{ tC}/\text{ha}$ (GIS Sol, 2013). An estimation of the carbon stock in the soil for arable lands was made using the tool SIMEOS AMG (<http://www.simeos-amg.org>), which simulates the accumulation of carbon in the soil, given: initial content of organic carbon in the soil (set at $10.7 \text{ gC}/\text{kg}$ as the average of different soil analysis from 4 farms), quality of the soil (average silt), climate (Île-de-France region), irrigation (assumed to be

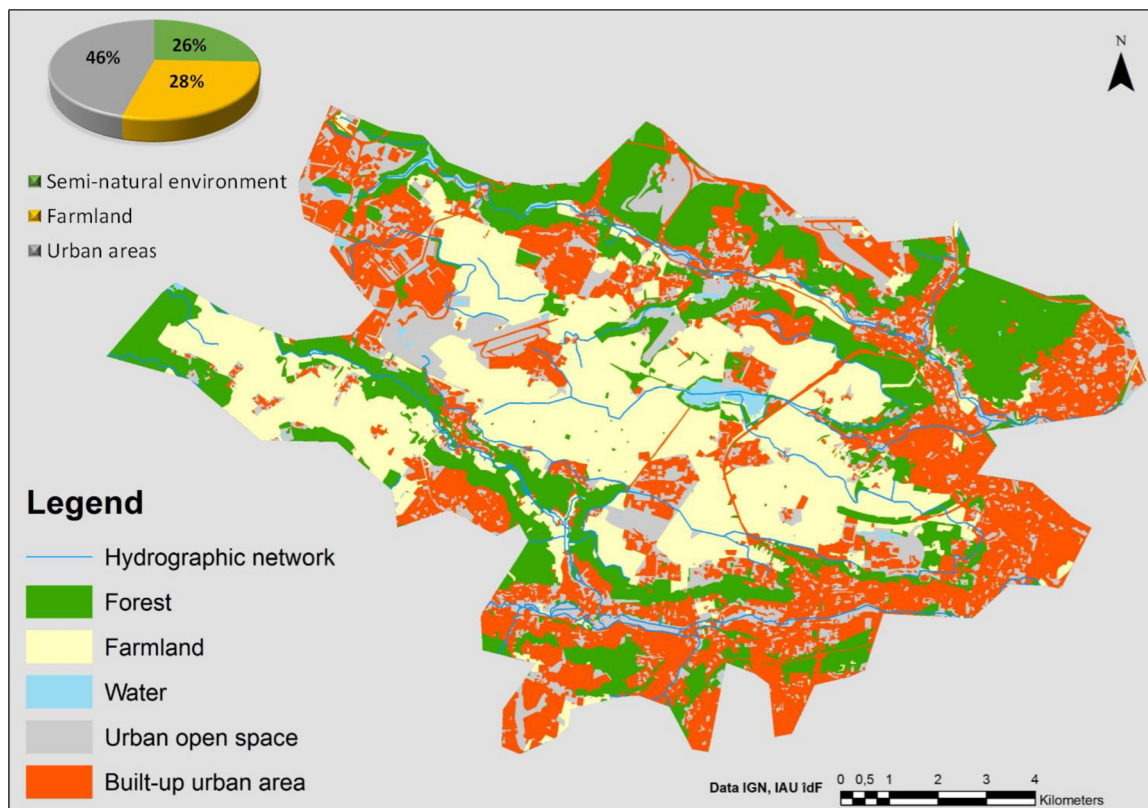


Fig. 2. Land use on the Saclay plateau. The related chart presents the distribution of areas devoted to semi-natural environment (forest and water), farmland and urban areas (urban open space and built-up area).

zero), crop rotation, and fertilizers used. For the last two items, the arable lands were divided into two groups of practices, depending on the type of farm. The first group was conventional agriculture: the farms were using common crop rotation (winter wheat, winter rapeseed, spring wheat, fodder corn, and winter barley) and intermediate crops (faba bean), and no organic fertilization. These practices are considered over 1860 ha. The second group refers to diversified agriculture: the farms were using organic fertilizers and less common crop rotation (additional inclusion of triticale). These practices are applied over 1440 ha. We thus obtained at equilibrium, two different carbon contents for the soil, and they were used to calculate the carbon stock in the arable land of the plateau.

2.2.2. Livestock

The number of animal farms and their respective time spent on grasslands and inside buildings are estimated from Tedesco et al. (2017), as well as feed importation and production. We estimated that, for manure production, a dairy cow produces 20 tons of manure per year, a heifer 9.4 t, a chicken 6.1 kg, a laying hen 8.4 kg, and a horse 9.0 t (SOeS, 2013). Furthermore, 11 kg/day/head of straw (produced inside the territory) are required for cattle litter (CA Indre, 2012) and 15 kg/day/head for horse litter (Hippolia, 2016).

Enteric fermentation is estimated in Table A4 (Appendix A). For cattle manure excreted on grasslands, 6.6% of its nitrogen is lost to the environment by NH_3 volatilization (Peyraud et al., 2012), 60% for poultry (SOeS, 2013) and 10% for horses (SOeS, 2013). Concerning its carbon, 13% is lost to the environment by volatilization for cattle (in the form of CH_4), 0.38% for poultry, and 1.5% for horses (SOeS, 2013). Manure excreted in the stables is used as organic fertilizer on arable land, except for 73% of horse manure which is exported. For cattle manure excreted in buildings, 31% of its nitrogen is lost to the environment (in the form of NH_3 , N_2 and N_2O , Peyraud et al., 2012), 50% for poultry, and 30% for horse (SOeS, 2013). Concerning its carbon,

16% is lost to the environment for cattle, 0.57% for poultry, and 27% for horses (in the form of CH_4 , SOeS, 2013). The carbon emitted in the atmosphere by the respiration of animals (CO_2) is deduced from the sum of the carbon received through alimentation, from which we subtract the carbon produced in the commodities (meat, eggs, milk) and the carbon emitted in the excreta and through enteric fermentation. Needs for water are estimated in Table A5 (Appendix A).

2.2.3. Population

To assess human food consumption, we calculated the number of meals taken each year on the Saclay plateau and the average quantity of the different product categories consumed per meal (Tedesco et al., 2017). We assumed that food waste at consumption level accounts for 13% of apparent consumption (Grizzetti et al., 2013). We added this percentage to ingested food calculations to evaluate the apparent consumption.

Biowastes produced (13% of the food products bought) are not reused within the study area. Wastewater is collected through the regional sewerage system and exported to wastewater treatment plants ten kilometers away from the Saclay plateau.

2.2.4. Green wastes and composting

Part of the green waste from green spaces is reused, thanks to a composting unit on one of the farms. Green waste composted in the composting unit comes not only from the Saclay plateau but also from outside (Tedesco et al., 2017). No attempt was made to calculate the part of green waste produced on the plateau but exported or re-used elsewhere.

The soil budget of green spaces was estimated in a similar way as for agricultural soils.

2.2.5. Forests

Areas and variety of trees in the forests were estimated using data from the IAU database (MOS, 2012 and ECOMOS, 2008). The forests were

assumed to be composed only of lobed-leaved trees. The volume per hectare was estimated at 165 m³/ha and the density at 850 kg/m³ (IGN, 2016). We used nitrogen (500 kg N/ha) and phosphorus (79 kg P/ha) contents of the forest wood from Ranger and Bonneau (1984). The carbon content of the wood was assumed to be 50% of dry mass (Boureau et al., 2017). Lixiviation of nitrogen and phosphorus, as well as symbiotic nitrogen fixation, was also provided by Ranger and Bonneau (1984), respectively 6 kg N/ha/year, 0.01 kg P/ha/year and 24 kN/ha/year. The amount of wood taken out by forest managers was calculated by subtracting nitrogen inputs (symbiotic fixation and atmospheric deposition – 10 kg N/ha/year for the latter) and nitrogen outputs (lixiviation). The carbon content of forest soil was estimated from Dupouey et al. (2000).

Harvest index, root shoot ratio, and humification coefficient for above and below ground parts of the trees were estimated from Le Noë et al. (2017), and are presented in Table A3 (Appendix A). They were used to estimate the input of fresh and humified organic carbon to the soil similarly to what has been done for agricultural soils. Carbon leaching was assumed to be 12 gC/m²/year for forests (Kindler et al., 2011). The carbon emitted into the atmosphere due to plant and soil respiration was approximated by subtracting the accumulation of carbon in the soil from the carbon content of the above and below-ground residues. The carbon capture due to net primary production was approximated by the carbon content of the amount of wood removed by forest managers.

2.2.6. Water system

The surface water system of the Saclay plateau is completely artificial and belongs to two watersheds: the Yvette basin as a minor surface contribution, directed artificially by ditches – though with intense leaking onto roads and southern slopes during heavy rainfalls –, and the Bièvre basin to the north. The ancient and patrimonial network of ditches is fed by water gathering from built or impermeabilized areas, and by the dense drainage network installed under all producing crop fields. A range of reservoirs of different sizes is used to buffer water flows for the purpose of flood management. Phreatic water dwells in the superficial formations with low, if any, lateral subsurface flows. Transpiration from crops is high but does not require irrigation due to the quality of the soil (except for market gardening, cf. Table A3, Appendix A). Some water infiltrates deeper (at around 80 +/- 20 mm/year, own estimation), through the semi-permeable “Argile à Meulière” formation, to Fontainebleau sands ground-waters that eventually seep to the rivers and marginally to a deeper limestone aquifer.

Human water uses include agriculture (arable lands and grasslands, market gardening), livestock farming (to water animals), industries and local population (drinking water, industrial use, geothermal heating, recreation such as golf), and green spaces (irrigation). To these compartments, we added the means of water transfer to depict the water flows: channels, lakes, water networks (drinkable water, wastewater, urban rain), drains, roads, slopes, soils (with the superficial phreatic table), phreatic tables of Fontainebleau sands and Albian (below the Fontainebleau Sands table).

The area taken into consideration regarding water flows was restricted to the top of the Saclay plateau, i.e. a surface area of 6800 ha (Avignon et al., 2015). The area of the two drainage basins (Yvette - 77% of the surface area - and Bièvre) was calculated using the IAU land-use database (MOS, 2012). Water balance was estimated from inputs of water (precipitation and drinkable water imports) and outputs (runoff to the rivers, evapo-transpiration, infiltration and wastewater exportation). Average precipitation (663 mm/year over the period 1945–2014) and evapo-transpiration (73.7% of precipitation) were estimated by Avignon et al. (2015). Transfers inside produced goods and internal trade-offs were disregarded. The local drinkable water used amounts to 170 l/day/cap (AESN, 2012), and we considered it as being transferred in place to wastewater without loss.

The amount of water that is drawn from the aquifer by industries is not precisely known, but at least three industries (CEA, CEPR and Danone) pump groundwater. The amount of water discharged to the

drainage basin of the Bièvre by the CEA is estimated at 800,000 m³/year (Avignon et al., 2015). Furthermore, two wells tap the Fontainebleau sands aquifer for agricultural purposes (but the amount seems negligible), one for golf irrigation (unknown amount), and one geothermal heating project plans to pump into the Albian aquifer and re-inject a volume of 1,700,000 m³/year.

3. Results

3.1. Nitrogen circulation

Nitrogen inputs relate to fertilization (mainly synthetic fertilizer and BNF and atmospheric deposition), animal feed and human food imports, as well as green waste (Fig. 3). Nitrogen outputs include agricultural production (arable land, grasslands and forestry), local population wastes managed at a regional scale, urine and feces, organic products for fertilization (manure and compost), and finally leaching and NH₃ volatilization and N₂O emission. The four highest nitrogen flows in the agri-food system are human food imports, urine and feces exports, synthetic fertilizers for arable land imports, and arable land production exports. They represent 69% of total flows. Moreover, in terms of nitrogen content, only 1.7% of local food consumption comes from local agriculture. These figures reveal a clear uncoupling³ between agriculture and local food consumption on the Saclay plateau, i.e. no significant connection in terms of material fluxes seems to exist between production and consumption.

We applied here the three indicators developed by Tedesco et al. (2017) to evaluate the degree of connection between local resources production and local needs: a production-based indicator “IP” (consumption from local production / total production) which represents the part of local production consumed locally; a consumption-based indicator “IC” (consumption from local production / total consumption) which represents the part of local production in the total local consumption (for food and fertilization); and a self-sufficiency capacity indicator “PC” which is defined here as the ratio of local production to local consumption.

Efficiency and self-sufficiency indicators for nitrogen are given in Table A6 (Appendix A). For fertilization, the link between local production and local consumption is relatively strong (IP = 44.3%). However, due to the high levels of synthetic fertilizer used on arable land and the very small proportion of legumes in crop rotations, local fertilizer production is insufficient to meet fertilization needs in terms of nitrogen (IC = 24.9%). The potential for a circular economy of nitrogen is nevertheless very high. Whereas local production could theoretically cover 56.3% of the local fertilization needs, recovery of nitrogen from human urine and feces for the local production would largely exceed the demand for agriculture fertilization (we would get a P/C value of 191%).

3.2. Phosphorus circulation

Phosphorus inputs relate to synthetic fertilizer for arable lands, animal feed and human food imports, as well as green waste (Fig. 4). Phosphorus outputs include agricultural production (arable land, grasslands, and forestry), local population wastes managed at a region scale, urine and feces, organic products for fertilization (manure and compost), and finally leaching and erosion. The four highest phosphorus flows in the agri-food system (75% of total flows) are human food imports, urine and feces exports, synthetic fertilizers for arable land imports and arable land production exports. Regarding phosphorus flows, these figures confirm the clear uncoupling between agriculture and local food consumption on the Saclay plateau.

Efficiency and self-sufficiency indicators for phosphorus are given in Table A7 (Appendix A). For fertilization, the link between local

³ Uncoupling can be defined as the absence of a connection (or the presence of a small connection) between two compartments of a system.

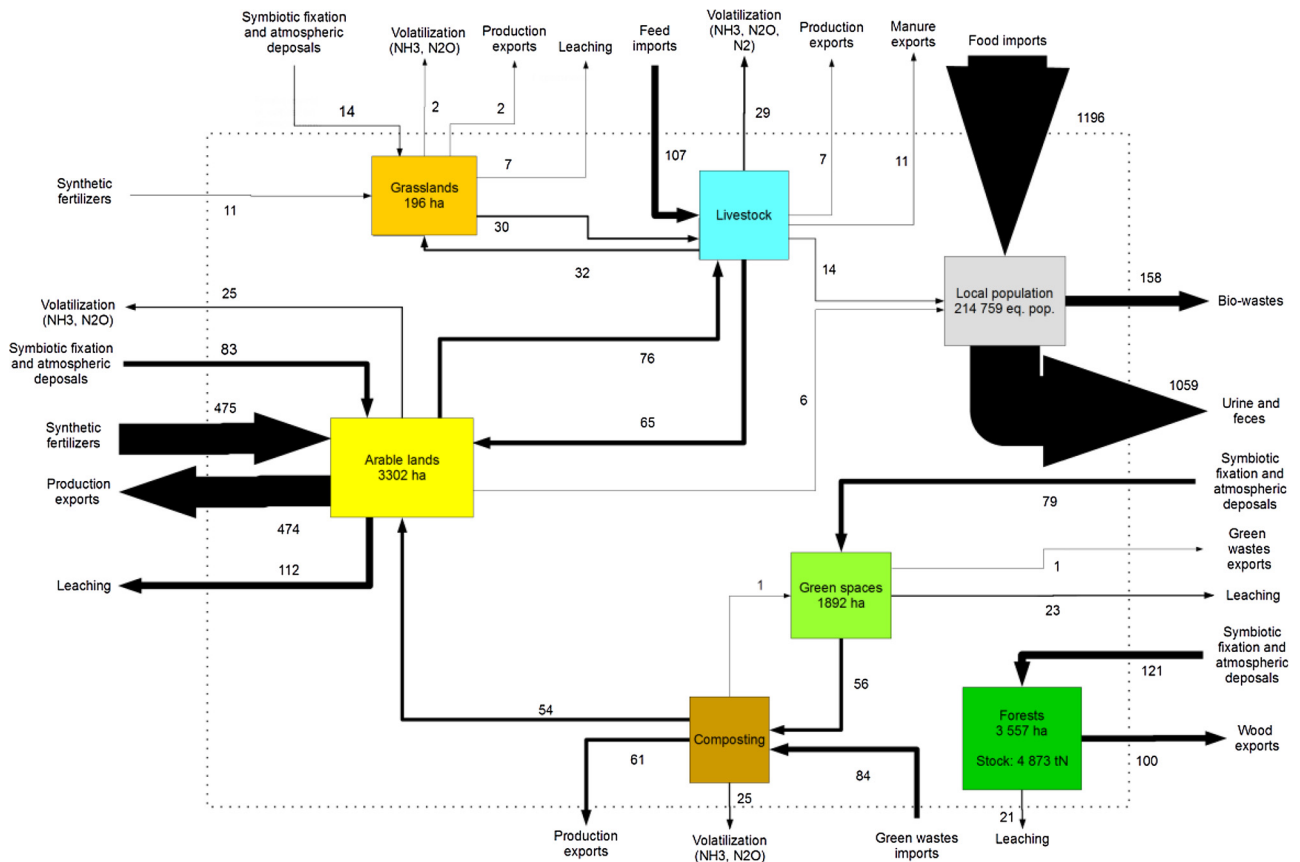


Fig. 3. Nitrogen circulation (tN/year), Saclay plateau.

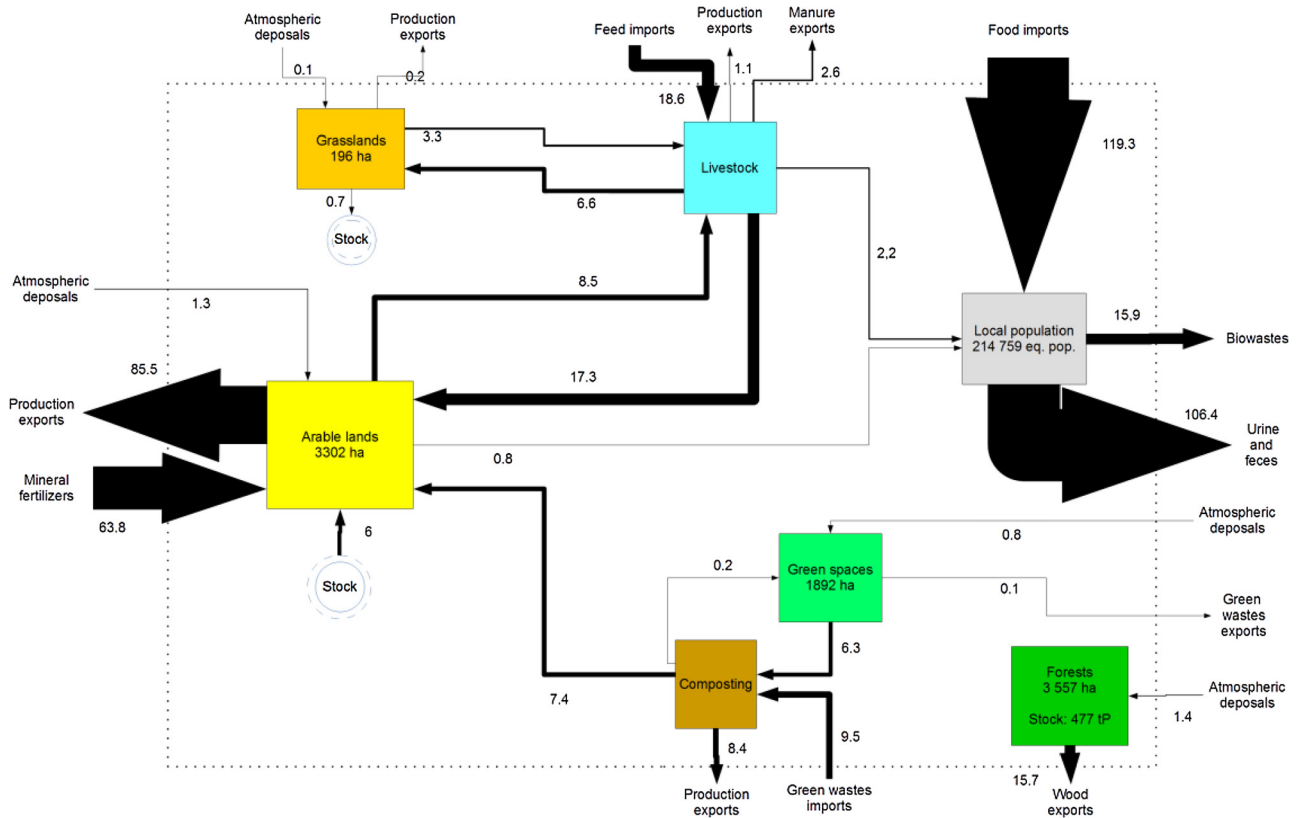


Fig. 4. Phosphorus circulation (tP/year), Saclay plateau.

production and local consumption is relatively strong (IP = 54.0%). However, due to the high levels of synthetic fertilizer use on arable land, local fertilizer production is insufficient to meet fertilization needs (IC = 33.1%). Similarly to nitrogen, local production could theoretically cover 61.2% of the local fertilization needs, but with the recovery of phosphorus from human urine and feces, the local supply of phosphorus for fertilization could exceed the demand (P/C equaling 173%).

3.3. Carbon circulation

Carbon inputs relate to net primary production, animal feed and human food importation, as well as green waste (Fig. 5). Carbon outputs include agricultural production (from arable land, grassland, and forestry), local population wastes managed at a region scale, urine and feces, organic products for fertilization (manure and compost), emissions and volatilization (CH₄ from breeding activities, CO₂ and CH₄ from composting activity, and CO₂ from liming of arable lands and grasslands) and finally respiration (plants, animal and population).

The four highest carbon flows in the agri-food system are primary production of arable lands (38,740 tonsC/year), net primary production of forests (36,880 tonsC/yr), CO₂ emission from respiration of forests (21,450 tonsC/year), and food imports (20,460 tonsC/year) accounting for 52% of all carbon flows. These figures also reveal a clear uncoupling, but the fact that primary production and respiration are such important flows that cannot be made circular limits the applicability of the analysis at the local scale. On the efficiency and self-sufficiency indicators (Table A8, Appendix A), it appears that, as no synthetic or mineral carbon is imported to fertilize the agricultural lands and green spaces, only local sources of carbon are used (IC = 100%).

However, there is some room to increase the carbon fertilization of the soil, as IP is only equal to 54.6%, due to exportation of compost and livestock manure. Furthermore, our calculations on the stock of carbon

of arable lands used two groups of practices for crop rotations and fertilizers: if the second group of practices that ensure a bigger stock of carbon were used on all farms, the stock of carbon of arable would increase to reach 190,460 tC (+8.5%). Such results could provide high incentives for a local carbon capture policy.

3.4. Water circulation

Water inputs relate to drinkable water and rain. Water outputs include evapotranspiration, runoffs into the Bièvre and Yvette rivers, and wastewater exports (Fig. 6). The value of the different flows is very uncertain. They generally suffer from an historical lack of measurement, apart from what is needed for major flood prevention (with dissymmetry between the Bièvre and the Yvette Rivers).

The two highest water flows in the agri-food system are rain (45,084,000 m³/yr) and evapotranspiration (33,227,000 m³/yr), accounting for 65% of all water flows. In parallel with carbon flows, these figures also reveal a clear uncoupling. Again, such important flows from rain and evapotranspiration cannot be made circular and limit the relevance of the analysis at the local scale. However, the rain which falls on the sealed urban surfaces (which represent 48% of the surface territory, Avignon et al., 2015) can be recovered for population, industrial or farming uses. This amounts to 15,949,000 m³/yr, i.e., higher than the industrial, population and farming water needs of the area.

Even if water scarcity has not emerged, water management is already an important issue. During the study, farmers and researchers made people and public authorities aware that water is already a critical resource on the Saclay plateau. Moreover, low flows in the rivers downstream (combined with temperature and dilution of pollution), floods and future competitive uses in a context of changes in climate and agricultural practices, might prove to be serious threats in the future.

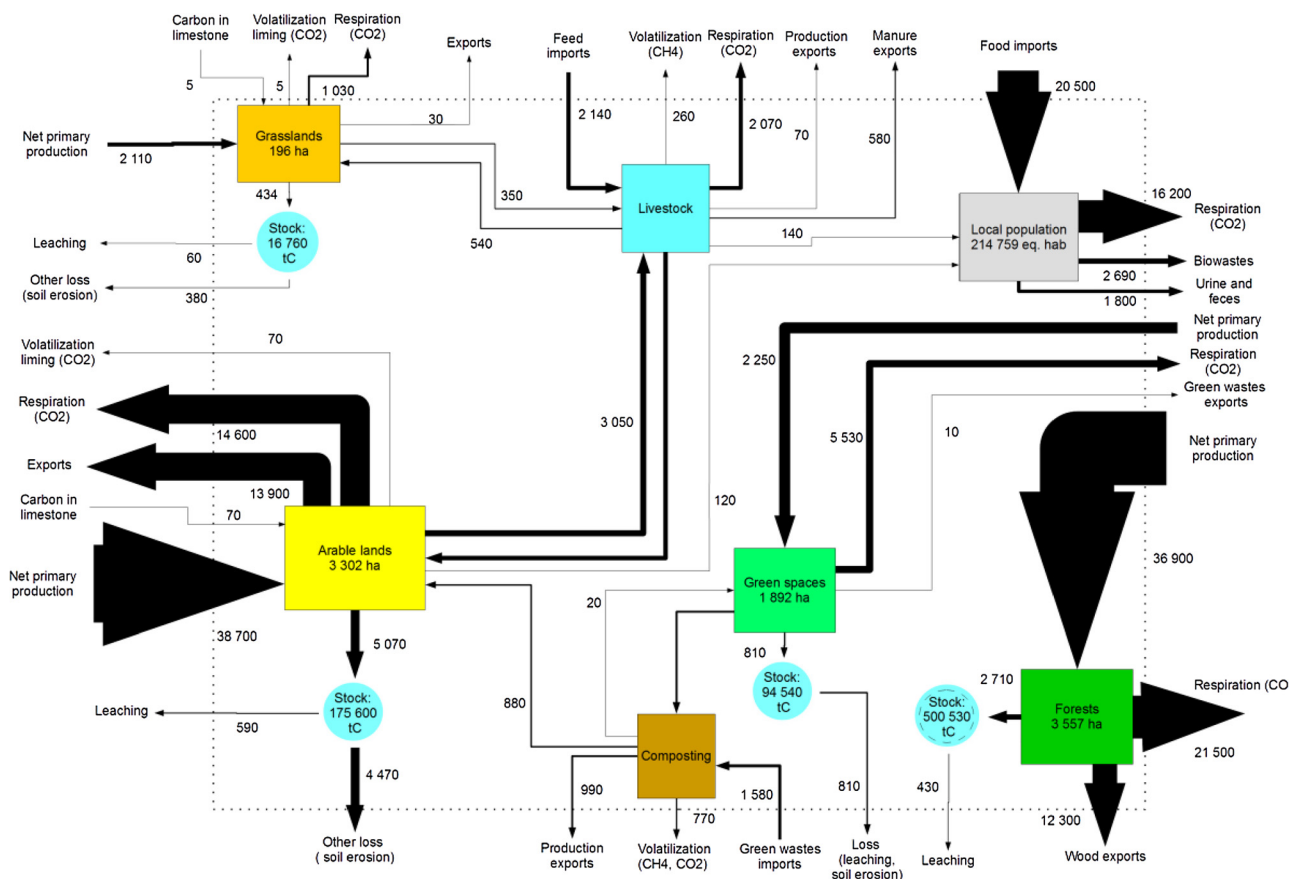


Fig. 5. Carbon circulation (tC/year), Saclay plateau.

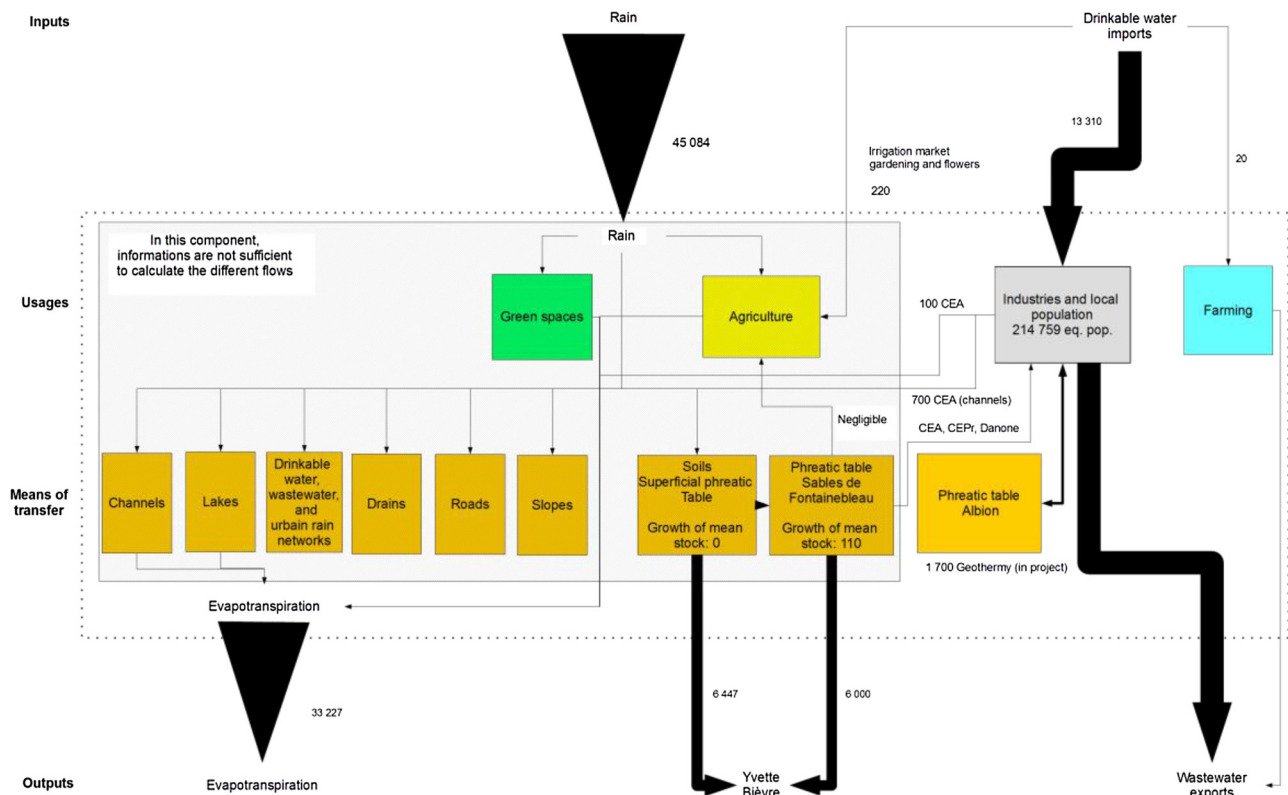


Fig. 6. Water circulation, Saclay plateau.

4. Discussion

The material flow analysis carried out here, shows that both for nitrogen and phosphorus, the main flows correspond to human food imports, urine and feces exports, synthetic fertilizers used in agriculture and agricultural production exports, evidencing the low level of internal connections characterizing this peri-urban system. These results invite us to explore pathways to create new internal flows and strengthen the existing ones. This seems possible because this territory has some specific features of peri-urban territories, i.e., large agricultural production and large population. Furthermore, the recoverability of carbon, nitrogen and phosphorus in waste has to be explored. Finally, metabolism analysis is directed for (i) increasing the stakeholder knowledge of their own territory, (ii) getting them aware about the current state of its metabolism and (iii) providing hints on how to improve the environmental impact of this territory. Territorial ecology is a research action approach, so that metabolism analysis should be coupled with the development of a participatory reflection about the territory and its future.

4.1. Studying the metabolism of a peri-urban territory

The study of the metabolism of such a small territory as the Saclay plateau raises questions about the relevance of the results and indicators that can be drawn from them. This is related to the argument that the smaller the territory, the higher the chances are of dependence on outside areas to sustain local activities. Thus, uncoupling flows may be in the nature of such small territories, and an apparently inefficient uncoupling at this scale does not prevent a closed and efficient loop at a higher scale.

But this argument depends on the activities carried out in the territory. Focusing on agricultural activities, Tedesco et al. (2017) showed that, except for grain production, the agricultural production of the Saclay plateau could not sustain its inhabitant's needs for food. This is because the agriculture is mainly dedicated to grain production, which

does not correspond to the diversified food consumption needs of a population. Even though the grain production could theoretically cover the local needs, it does not benefit to the local population as this local grain production is mainly sold outside the plateau through long supply chains (regional including the Paris region, and international exports). On the other hand, in such a densely populated peri-urban territory, the amount of biowaste and wastewater is significant and could support agricultural needs for fertilization. Moreover, if the agricultural production were more diversified, a substantial part of the local population's food consumption could come from local agriculture. From this perspective, a large population would be actually a blessing.

Hence, for a territorial ecology study, the scale is less important than the question on the potentiality of the territory to close the loops of matter and energy. Peri-urban territories, in this respect, appear to be highly suitable for such studies, as they can have both a large agricultural area which can sustain a high number of inhabitants, and a large number of inhabitants to provide nitrogen, phosphorus and carbon back to agricultural land, once systems of nutrient recovery from biowaste and human excreta have been implemented. Even if peri-urban territories are usually associated with high environmental impacts, and considering that environmental impacts should therefore be carefully assessed before drawing any conclusions, the coupling of urban and rural areas can lead to an optimized use of resources which would not be possible in only urban or only rural territories. Whereas Treadwell et al. (2018) reported an example of P metabolism in a city, where the recovery would exceed the demand, Wielemaker et al. (2018), showed the potentiality to increase the recovery capacity with urban agriculture; for an example of N, P and C metabolism of rural regions in France, see Le Noë et al., (2017).

Therefore, without calling for the construction of more peri-urban areas, the analysis of the Saclay plateau shows that in already existing peri-urban areas there is room for improving metabolism, so that more internal flows are built and environmental impacts decreased.

4.2. Recoverability of carbon, nitrogen and phosphorus in waste

The possible recovery of nitrogen and phosphorus in biowaste and wastewaters is a distinct issue from that of its potential. Currently, in the Paris region, biowastes are scarcely recovered and applied back to agricultural soils. They are mainly incinerated, which means that their nitrogen and carbon content is released into the atmosphere, while ashes containing phosphorus are landfilled (Esculier and Tabuchi, 2015). The French law on energetic transition (“Loi n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte”) requires that waste management public services enable all citizens to have a biowaste recovery option by 2025. Unfortunately, this law is mainly carbon-oriented and does not recognize nitrogen and phosphorus recovery as an important issue.

A more systematic recovery of biowaste nutrients (e.g., through source separation of biowaste followed by composting or methanization) would increase the recovery rates of nutrients, possibly achieving close to 100% of recycling for the phosphorus flow. For nitrogen and carbon, recovery rates depend on the technology used. Composting can lead to losses of nitrogen in the form of ammonia: 30% of nitrogen loss is a common value but losses can vary widely, depending on the conditions of the composting process (Beck-Friis et al., 2001). In the case of composting at large scale, ammonia recovery from gaseous emissions is most suitable. Biowaste can also be methanized in which case the nitrogen recovery rate depends on digestate issues. As digestion at a wastewater treatment plant that does not recover nitrogen from digestate would be a poor solution in terms of nutrient recovery, digestion in a facility that recovers nitrogen should be promoted.

The efficiency of carbon recovery is higher in methanization since organic carbon is converted to highly energetic CH₄. However, both composting and methanization cannot yield 100% recovery of carbon in a reduced form since these biological processes unavoidably generate CO₂ emissions.

Concerning the wastewater, current treatment technologies focus on the removal of nutrients to reduce surface and underground water pollution, rather than on their recycling. Presently for nitrogen, the recycling rate in agriculture is negligible for the Paris region: only 5% of nitrogen is recovered in sewage sludge and spread on agricultural lands. 62% of it is released into the environment in gaseous form during the wastewater treatment process (nitrification followed by denitrification, mainly in the form of inert N₂ but also as NH₃ and N₂O), and the rest discharged into water bodies. For phosphorus present in wastewater, the recycling rate for wastewater plants of the Paris region is about 40%; 19% of the phosphorus is discharged into water bodies and 41% is incinerated. For carbon, the recycling rate is about 15% (Esculier and Tabuchi, 2015).

These figures highlight the fact that the potential to recover N, P and C from wastewater for agricultural purposes is not high, if we rely on existing techniques only, even if a new wastewater treatment plant were implemented on the Saclay plateau. A more promising pathway could be to implement a recovery of human urine and excreta at the source. Furthermore, as the composting unit of the Saclay plateau functions at full capacity, an increase of the composting of biowaste would require new composting units on the plateau.

Yet, as virtuous as such a re-cycling of nutrients may be, the presence of chemical and biological molecules in wastewaters (e.g., antibiotics) must be taken into account (Zhu et al., 2017). Re-use of urban waste remains a sensitive issue, and the sensitivity of this issue has actually increased in our post-industrial context, compared to the pre-industrial one, where materials were less complex, mostly organic, and where urban wastes were ones of the first resources used to increase the quality of the land for the farmers in the peri-urban areas. Nowadays, urban wastes also contain inorganic or toxic contaminants.

Furthermore, the reintegration of these complex materials for agricultural fertilization is not straightforward for the farmers, as they are used to manage pure substance flows of fertilizers (N, P, K). They do

not have much technical references about the use of these new materials, whose mineralization highly depends on pedologic and climatic conditions. But these barriers could be overcome if environmental awareness about the impact of the production and the leaching of mineral fertilizers is increased, and if the scarcity of mineral fertilizers such as phosphorus increases.

4.3. Interest of the metabolism approach for discussion with stakeholders

The goal of the study of N, P, C and water circulation in a peri-urban territory is first to highlight the potential of such a territory for the construction of a more efficient metabolism, in order to reduce its environmental impacts. The logical following steps, once the metabolism has been described, is to develop scenarios of alternative metabolisms, to assess their associated environmental impacts, and then to decide on a pathway and a strategy to implement it. Different visions are developed in the field of territorial ecology about how to go from the analysis of the metabolism to action within the territory (Madelrieux et al., 2017). These visions depend on: (i) positions on the kind of sustainability that should be sought, either weak (e.g., see Allenby, 1992) or strong (e.g., see Ehrenfeld, 2004); (ii) positions on how prescriptions should be constructed, either through an “objective” scientific point of view (e.g., see Boons and Roome, 2001), or from a “subjective” participative process designed to include all relevant actors of the territory (e.g., see Cerceau et al., 2014); and (iii) positions on how the policy should be implemented, either through planning, or in a more liberal way (Vivien, 2003).

It is essential to have these different visions in mind during the construction of the description of the metabolism, if the goal is to serve action. In this respect, we believe that a pathway for future actions within peri-urban territories would be to develop a foresight approach that would link the study of the present metabolism with the reconstruction of past socio-ecological dynamics. Developing radical visions – if possible in a participative way –, would force the stakeholders to review their beliefs about the future of the territory, and help them to construct a shared scenario of what they want for the territory (Rhisiart et al., 2015).

In the Saclay plateau, this post-analysis was made with the help of the territorial association Terre & Cité. With their help, a workshop was conducted to study the preliminary results, discuss them between researchers and with actors of the territory, and construct scenarios of the evolution of the Saclay plateau’s metabolism in 2050.

The method for the construction of the scenarios was to highlight already present dynamics and weak signals, and to show how their underlying logics could transform the territory, if each of them were pushed toward their extreme. To describe them is beyond the scope of this article, but these scenarios were not necessarily realistic, i.e., they were neither supposed to reflect a consensus among the stakeholders nor the state of discussion between them. The three scenarios were then presented to different groups of actors of the Saclay Plateau. All scenarios were perceived as plausible, at least for one group of actors, i.e., representative of current trends. But each scenario was also criticized as a rupture from the existing situation by at least one group of actors. This method was thus useful to reveal present values and strategies of the actors that could serve as a basis to construct a common strategy around a shared perspective on the future of the territory.

5. Conclusion

Environmental issues, such as excess of nitrogen in the biosphere, water eutrophication, carbon emission in the atmosphere or hydrological impacts, are intrinsically linked to human activities, lifestyles and urban development. Facing these issues, peri-urban areas are not receiving as much attention as urban areas. In this research, we have focused on a French peri-urban area in the Parisian region, the Saclay plateau. Considering this territory as a system organizing agricultural, food and waste flows, we have analyzed its metabolism through N, C, P and water flows. Our findings provide strong evidence that the metabolism of the territory is largely open,

i.e., the main flows are input and output flows with small or nonexistent internal flows. This is particularly the case for nitrogen and phosphorus flows. The same findings hold for carbon flows although primary production and respiration play a major role in the carbon metabolism. Besides the uncertainty of the available data, water flows also reveal a clear uncoupling between compartments of the system.

A high potential for reconnections of the different flows is evidenced, mainly due to the presence of large areas of agricultural lands and large populations. Implementation of recovery of biowaste, of human excreta at source, as well as of rain, could help to realize this potential. As carbon and water flows cannot easily be made circular, the interest for a circular approach at the local scale is limited. This analysis is far more relevant for N and P flows. Their recovery in biowastes and in the exports of manure and green waste compost would be enough to double the present consumption of local fertilizers on the territory, resulting respectively in 56% and 61% of the fertilization needs. If recovery of human excreta at source is furthermore implemented, the fertilization needs would be more than satisfied.

Nevertheless, each substance (N, P, C and water) is circulating inside complex materials that make them difficult to be mobilized in new internal connections (e.g., in the case where contaminants or pollutants are present in the materials, [Baxter et al., 2017](#)). For carbon flows, there is no fertilization needs, but the increase of the carbon stock of the soil already discussed as a potential policy goal (see for instance the 4 per 1000 initiative, launched by France during the Climate Conference COP21 in Paris in 2015), could promote recovery of the carbon content of biowaste and green waste compost and manure currently exported.

Appendix A

Table A1

Nitrogen, phosphorus and carbon content (%) in food commodities and waste.

	Nitrogen content (% of mass)	Phosphorus content (% of mass)	Carbon content (% of mass)	References
Wheat (dry)	1.7	0.32	48	Sauvant et al. (2004)
Corn (dry)	1.3	0.26	48	Sauvant et al. (2004)
Rapeseed (dry)	3.1	0.66	48	Sauvant et al. (2004)
Barley (dry)	1.6	0.34	48	Sauvant et al. (2004)
Faba bean (dry)	4.2	0.47	48	Sauvant et al. (2004)
Triticale (dry)	1.5	0.35	48	Sauvant et al. (2004)
Alfalfa (dry)	3.3	0.24	48	Sauvant et al. (2004)
Sugar beet (fresh)	1.3	0.09	48	Sauvant et al. (2004)
Grassland production (dry)	2.7	0.29	48	Sauvant et al. (2004) (80% grass, 10% alfalfa, 10% clover)
Vegetables (fresh)	0.58	0.061	8.1	Ciquel (2013)
Fruits (fresh)	0.11	0.016	6.3	Ciquel (2013)
Milk (fresh)	0.53	0.087	5.2	Nitrogen : Courtet-Leymarios (2010) ; phosphorus and carbon: Ciquel (2013)
Beef (fresh)	3.9	0.17	21	Ciquel (2013)
Chicken (fresh)	4.6	0.22	19	Ciquel (2013)
Eggs (fresh)	2.0	0.19	16	Ciquel (2013)
Bio-waste (fresh)	0.57	0.057	9.7	Weighted average from food products consumed by the human population of the plateau. Nitrogen and carbon values are compatible with data from Beck-Friis et al. (2001) .
Green waste (dry)	2.5	0.29	48	Sauvant et al. (2004) (90% grass, 5% alfalfa, 5% faba bean)
Wood (fresh)	0.36	0.056	50	Nitrogen and phosphorus : Ranger, and Bonneau, (1984) ; carbon: Boureau et al. (2017)
Green waste compost (fresh)	0.8	0.11	13	Nitrogen : Chabalier et al. (2006) ; phosphorus: own calculation, compatible with data from Chabalier et al. (2006) ; carbon: Hartley et al. (2009)
Horse manure (fresh)	0.42	0.11	10	Nitrogen : Martin-Rosset et al. (2013) ; phosphorus: own calculation, compatible with data from Martin-Rosset et al. (2013) ; carbon: Mönch-Tegeger et al. (2013)
Beef manure (fresh)	1.0	0.19	10	Nitrogen: Peyraud et al. (2012) ; phosphorus: own calculation; carbon: Giroux and Audesse (2004)
Poultry manure (fresh)	3.9	1.4	48	Nitrogen: Gac et al. (2007) ; phosphorus: own calculation; carbon: Guerra-Rodríguez et al. (2001)
Urine and faeces (fresh)	0.91	0.091	1.5	Own calculation. Nitrogen and phosphorus values are compatible with nitrogen data from Rose et al. (2015) ; and carbon value is compatible with data from Esculier and Tabuchi (2015)

As for water, the recovery of the rain on sealed urban surfaces could cover the industrial, urban and farming needs.

The territorial ecology approach followed in this article offers strong support for a scientific approach to analyze a territory through its metabolism. As a next step, a discussion possibly supported by the construction of radical scenarios, would seek to reveal both the future impacts of present dynamics and the reactions of actors facing these future impacts of the territory. More research needs then to be done on the link between the analysis of present metabolism, and the construction of a strategy to improve it.

Declarations of interest

None.

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Table A2
Volatilization of crop residue parameters (from De Klein et al., 2006).

Crop	Nitrogen volatilization due to crop residue (kgN/ha/year)
Permanent grassland	0.68
Temporary grassland	0.14
Common wheat	1.1
Maize	0.86
Barley	0.69
Triticale	0.55
Faba	0.57
Alfalfa	1.3
Rapeseed	0.42
Sugar beet	0.015
Orchard	0
Market gardening	3.1

Table A3
Harvest indexes, root shoot ratios, humification coefficients (compiled by Le Noë et al., 2017).

	Harvest index	Root shoot ratio	Humification coefficient above-ground part	Humification coefficient below-ground part
Wheat	0.45	0.2	0.15	0.15
Corn	0.52	0.24	0.15	0.15
Rapeseed	0.29	0.2	0.15	0.15
Barley	0.45	0.21	0.15	0.15
Faba bean	0.39	0.6	0.12	0.15
Triticale	0.45	0.2	0.15	0.15
Alfalfa	0.8	1.2	0.12	0.2
Sugar beet	0.51	0.8	0.08	0.15
Temporary grassland production	0.8	0.8	0.12	0.2
Permanent grassland production	0.5	1.6	0.12	0.2
Vegetable	0.3	0.15	0.12	0.15
Fruit	0.35	0.2	0.12	0.15
Manure and compost supplied to arable lands and green spaces	–	–	0.46	–
Direct grazing extraction on grasslands	–	–	0.26	–
Green spaces production	0.5	1.6	0.12	0.2
Forest	0.4	0.2	0.12	0.15

Table A4
Enteric fermentation from breeding (SOeS, 2013).

	Enteric fermentation (kgCH ₄ /head/year)
Dairy cow	122
Heifer under two years	24.0
Heifer between one and two years	60.2
Male bovine under one year	25.9
Laying hen	0.10
Chicken	0.00
Horse	20.7

Table A5
Water needs for breeding (Ward and McKague, 2007) and for market gardening (authors' calculation).

	Water needs (kg/head/day for breeding)
Dairy cow	115
Heifer	25.4
Male bovine under one year	9.05
Laying hen	0.25
Chicken in summer	0.45
Chicken in winter, spring, autumn	0.28
Horse	32.5
Market gardening	3 500 m ³ /ha/year

Table A6
Efficiency and self-sufficiency indicators for nitrogen flows.

EFFICIENCY INDICATORS $lp = \text{Local consumption}/\text{Total production}$; $lc = \text{Local consumption}/\text{Total consumption}$

Nitrogen	lp	lc
Fertilization <i>Without urine and faeces</i>	44% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+(exported biowaste and green wastes)*(1-rate of volatilization of nitrogen during the composting process))	25% consumption of local fertilizers from livestock and composting/total consumption of fertilizers (local fertilizers+ synthetic fertilizers)
Fertilization <i>With urine and faeces</i>	13% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+(exported biowaste, green wastes, urine and faeces)*(1-rate of volatilization of nitrogen during the composting process))	

SELF-SUFFICIENCY CAPACITY INDICATORS P = Production ; C = Consumption

Nitrogen	P/C	
Fertilization <i>Without urine and faeces</i>	56% total production of fertilizers (livestock+composting+(exported biowaste and green wastes)*(1-rate of volatilization of nitrogen during the composting process))/total consumption of fertilizers (local fertilizers+ synthetic fertilizers)	44% 1-P/C
Fertilization <i>With urine and faeces</i>	191% total production of fertilizers (livestock+composting+(exported biowaste, green wastes, urine and faeces)*(1-rate of volatilization of nitrogen during the composting process))/total consumption of fertilizers (local fertilizers+ synthetic fertilizers)	-91% 1-P/C

Table A7
Efficiency and self-sufficiency indicators for phosphorus flows.

EFFICIENCY INDICATORS $lp = \text{Local consumption}/\text{Total production}$; $lc = \text{Local consumption}/\text{Total consumption}$

Phosphorus	lp	lc
Fertilization <i>Without urine and faeces</i>	54% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+exported biowaste and green wastes)	33% consumption of local fertilizers from livestock and composting/total consumption of fertilizers (local fertilizers+ mineral fertilizers)
Fertilization <i>With urine and faeces</i>	19% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+exported biowaste, green wastes, urine and faeces)	

SELF-SUFFICIENCY CAPACITY INDICATORS P = Production ; C = Consumption

Phosphorus	P/C	
Fertilization <i>Without urine and faeces</i>	61% total production of fertilizers (livestock+composting+exported biowaste and green wastes)/total consumption of fertilizers (local fertilizers+ mineral fertilizers)	39% 1-P/C
Fertilization <i>With urine and faeces</i>	173% total production of fertilizers (livestock+composting+exported biowaste, green wastes, urine and faeces)/total consumption of fertilizers (local fertilizers+ mineral fertilizers)	-73% 1-P/C

Table A8

Efficiency and self-sufficiency indicators for carbon flows.

EFFICIENCY INDICATORS		
Carbon	$lp = \text{Local consumption/Total production}$	$lc = \text{Local consumption/Total consumption}$
Fertilization <i>Without urine and faeces</i>	55% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+(exported biowaste and green wastes)*(1-rate of volatilization of carbon during the composting process))	100% consumption of local fertilizers from livestock and composting/total consumption of fertilizers (local fertilizers)
Fertilization <i>With urine and faeces</i>	45% consumption of local fertilizers from livestock and composting/total production of fertilizers (livestock+composting+(exported biowaste, green wastes, urine and faeces)*(1-rate of volatilization of carbon during the composting process))	
SELF-SUFFICIENCY CAPACITY INDICATORS		
Carbon	P/C P = Production ; C = Consumption	
Fertilization <i>Without urine and faeces</i>	183% total production of fertilizers (livestock+composting+(exported biowaste and green wastes)*(1-rate of volatilization of carbon during the composting process))/total consumption of fertilizers (local fertilizers)	-83% 1-P/C
Fertilization <i>With urine and faeces</i>	220% total production of fertilizers (livestock+composting+(exported biowaste, green wastes, urine and faeces)*(1-rate of volatilization of carbon during the composting process))/total consumption of fertilizers (local fertilizers)	-120% 1-P/C

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