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ORIGINAL ARTICLE

The food-print of Paris: long-term reconstruction of the nitrogen flows imported into the city from its rural hinterland

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Abstract Between the tenth and twentieth century the population of Paris city increased from a few thousand to near 10 million inhabitants. In response to the growing urban demand during this period, the agrarian systems of the surrounding rural areas tremendously increased their potential for commercial export of agricultural products, made possible by a surplus of agricultural production over local consumption by humans and livestock in these areas. Expressed in terms of nitrogen, the potential for export increased from about 60 kg N/km^2/year of rural territory in the Middle Ages, to more than 5,000 kg N/km^2/year from modern agriculture. As a result of the balance between urban population growth and rural productivity, the rural area required to supply Paris (i.e. its food-print) did not change substantially for several centuries, remaining at the size of the Seine watershed surrounding the city (around 60,000 km^2). The theoretical estimate of the size of the supplying hinterland at the end of the eighteenth century is confirmed by the figures deduced from the analysis of the historical city toll data (octroi). During the second half of the twentieth century, the 'food-print' of Paris reduced in size, owing to an unprecedented increase in the potential for commercial export associated with modern agricultural systems based on chemical N fertilization. We argue that analysing the capacity of territories to satisfy the demand for nitrogen-containing food products of local or distant urban population and markets might provide new and useful insights when assessing world food resource allocation in the context of increasing population and urbanization.

Keywords Paris · Seine basin · Ecological footprint · Food-print · Nitrogen · Autotrophy/heterotrophy

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Introduction

A city can be defined as a grouping of population which does not produce its own means of food subsistence (Asher 2001). It therefore depends upon surrounding rural areas for the provision of food resources, as well as fiber, fuel, and building materials. In a work often considered to have laid the basis of economic geography, Von Thünen (1826) deduced from an idealized economic model based on early nineteenth century agriculture and transport costs, that a city would tend to be surrounded by several concentric rings of farming activity, beginning with market gardening and dairy farming, followed by forestry, cereal production, and finally cattle breeding. In the present day, cheap transportation, preservation techniques and the opening of the global market economy have considerably scattered the distribution of agricultural areas that supply food to cities, but have certainly not reduced the dependence of cities on such regions, wherever they are located, nor the pressure exerted on the latter by urban markets. Wakernagel and Rees (1996) introduced the concept of the ecological footprint which provides an account of the total area of productive surfaces required to produce, under prevailing world technology, the resources consumed by a country or a city. Feeding modern cities is associated with one-third to half of the global ecological footprint, ranging world-wide from 0.8 to 3.8 global-hectares per inhabitant (WWF 2002). This simple "footprint" indicator, however, fails to fully describe the complexity of the relationships that a city establishes with its rural hinterland for the supply of food, nor how, over time, these relationships impact upon the development of both the city and the countryside.

Our goal here is to examine how the city of Paris has grown up in parallel with the development of its surrounding rural landscape over the long time scale of the last Millennium. In particular, we analyse (1) how closely dependent the past development of the city has been on the progress and specialization of agriculture in the Parisian basin, as well as (2) the importance of the growing urban food demand on the development and spatial distribution of farming practices in the surrounding rural regions. For this purpose, we have collated available information allowing a comparison of changes in the food requirement of the growing urban population and in the potential for commercial export of the Seine basin rural territory throughout a period beginning around the tenth century to the present day. Our approach is based on historical biogeochemistry. Since nitrogen is an essential constituent of the human diet as well as the most limiting factor in agricultural production in temperate regions, we elected to describe the exchanges between the countryside and the city in terms of nitrogen flows. Our analysis thus contributes to a better description and understanding of the profound alterations to the global nitrogen cycle caused by human development (Galloway et al. 1995; Galloway and Cowling 2002). As underlined by Smil (1999), agricultural production is by far the largest cause of the doubling in the amount of reactive nitrogen entering the biospheric cycle compared to pre-industrial conditions. This process, operating through enhanced biological N_2 fixation and industrial N fertilizer production, has resulted in several environmental dysfunctions (Galloway et al. 1995; Galloway and Cowling 2002). Today, more than half of the crops produced in rural areas of the world are consumed in urban zones, which set important constraints on the mode of agricultural production at both the regional and global scales.

Sources and methods

Estimating the flux of material between a city and its hinterland over a millennium obviously requires a large diversity of sources as well a close interdisciplinary collaboration. Paris and the rural areas of the Parisian basin have been the subject of an extensive historical literature, including excellent reviews, which provide the required historical background knowledge necessary to the approach described in this report. Among the sources available, a number of studies have been particularly useful. Favier (1997) published a synthesis of two Millennia of Parisian history while, concerning the Middle Ages and the Modern Epoch, the works by Fourquin (1956), Jacquart (1974) and Goubert (1982) were quite useful. The recent works of Kaplan (1988) and Abad (2002) additionally provided an extremely detailed analysis of the food supply of Paris at the end of the eighteenth century. Barles (2005, 2007) and Barles and Lestel (2007) closely analysed the food consumption and nitrogen metabolism of Paris during the nineteenth century while, from a more general perspective, authors such as Mazoyer and Roudart (1998) with their socio-ecological analysis of agrarian systems, opened the way to the historical-biogeochemical approach we developed here in the case of the Parisian basin. The principles and methods of material flow analysis and spatial imprint evaluation have been described in detail and applied to the special case of Linköping (Sweden) for the period 1870–2000 by Schmid-Neset (2005).

As stated earlier, our approach consists of comparing, in terms of nitrogen flows, the food demand for consumption in the city with the ability of the surrounding rural territories to meet that demand through commercial export. We used conversion factors compiled from various sources to convert data expressed in specific physical units into nitrogen (Table 1).

Population and food requirement of Paris

Paris conurbation presently numbers 9,650,000 inhabitants if only the contiguous urban area is considered, or 11,175,000 inhabitants if the whole metropolitan area is taken into account (INSEE 2006). The figure for *intra muros* Paris is 2,125,800 (INSEE 2006). After the early eleventh century, when the population of Paris was estimated to be only a few thousand inhabitants (Favier 1997), a period of rapid population growth occurred, linked to the status of capital city conferred to Paris under the reign of Philippe Auguste (1180–1223). This population expansion continued until the early fourteenth century when it reached 200,000 capita (Fig. 1). A century of crisis then followed in which war and plague severely decreased the population of both the city and the rural regions (Bois 1981; Jacquart 1974), but the urban population growth resumed at the beginning of the fifteenth century. It decreased again in the period 1562–1598 (French Wars of Religion), then increased continuously until Paris numbered more than 600,000 inhabitants at the time of the 1789 French Revolution. A fivefold increase then occurred

Table 1 Nitrogen content of food and agricultural products (in % fresh weight of the cropped or consumed product), and other figures related to nitrogen flows in agrarian systems. (Compiled from Baccini and Bruner 1991; Soltner 2005; Smil 1999)

Product	N content, %
Foodstuff	
Cereals	1.8
Bread	1.4
Potatoes	0.3
Fresh vegetables and fruits	0.4
Dry vegetables	2.1
Meat	3.4
Fish and seafood	3.4
Eggs	2.1
Milk	0.5
Cheese	3.7
Butter	0.14
Beer	0.05
Wine	0.035
Feedstuff	
Hay	1.3
Straw	0.5
Firewood	0.2
Cultivated plants	
Colza	3.7
Sunflower	3.5
Beet	1.5
Livestock feed requirement	*kg N/capita/year*
Cattle	95
Pigs	6.5
Sheep and goats	5.5
Horses	45
Poultry	0.3
Rabbits	0.3

during the nineteenth century, followed by a further doubling during the twentieth century.

On the wider scale, the city accounted for less than 5% of the total population of the Seine river watershed (about 60,000 km^2 surrounding Paris; Fig. 1) in the thirteen century, but reached 20% at the end of the eighteenth century. From that time on, growth has been restricted to the urban population (Fig. 1), which today represents 85% of the population of the watershed area.

The present per capita domestic food consumption can be evaluated by two kinds of statistical inquiries based on: (1) a record of the effective individual diet of a sample of the population (sample method) and (2) the balance of national production comparing import and export of food products (balance method). The latter method provides significantly higher figures than the former since it includes a number of losses during food storage, preparation and commercialisation. Thus, Table 2 shows that the gross per capita N-food consumption in France (balance method) increased from 15 to 22 g N/day between 1950 and 2000, while the effective per capita consumption based on the INSEE enquiries (sample method) varied only slightly around a figure of 12 g N/capita/day from 1970 to 1990 (INSEE 1995). The latter figures, however, might be underestimated as they do not take into account food consumed outside of the home which represents an increasing part of the diet. It is worth noting that the mean per capita rate of nitrogen excretion calculated from wastewater analysis lies between 11 and 15 g N/capita/day (Servais et al. 1999; Garnier et al. 2006).

For historical periods, only the balance method is applicable. In the case of Paris, this process is facilitated by the fact that, until World War II, most goods entering the city were subject to a city toll (octroi), the statistics of which are available from the end of the eighteenth century (Feugère 1904). Barles (2007) analysed the available data from 1801 to 1914 and the data from the eighteenth century, including those already compiled by Lavoisier (Philippe 1961), were discussed by Abad (2002) (Table 2). Hay and other feed for horses were an important component of the city's demand for agricultural products. Barles (2007) has evaluated the extent of their import in the nineteenth century which subsequently becomes negligible in the second half of the twentieth century. Firewood for heating, cooking and baking must also be taken into account, the annual demand for which was estimated as

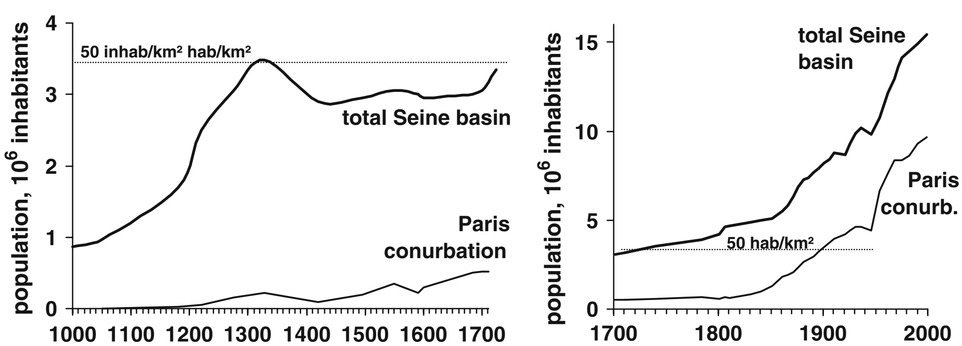

Fig. 1 Population growth in the Paris conurbation and in the Seine basin area during the last millennium. Synthesis of data compiled by Fourquin (1956); Croze (1988); Levasseur (1889); Favier (1997); Barles (2007); INSEE (2007); Dupeux (1981)

Table 2 Paris per capita consumption rate of nitrogen in food, feed and firewood from the ninenteenth to the twentieth century. estimated (1) from 1785 to 1889 from the data of Paris city toll statistics and (2) from 1950 to 2000 from the data of national French domestic consumption (INSEE 2000)

	1785	1820	1854	1889	1950	1960	1970	1980	1990	2000
Human food, kg N/capita/year										
Bread and other cereal products	2.26	2.57	2.52	2.04	1.94	1.69	1.48	1.42	1.38	1.34
Potatoes	0.00	0.10	0.07	0.09	0.46	0.38	0.38	0.27	0.19	0.56
Fresh vegetables and fruits	0.20	0.20	0.76	0.20	0.28	0.38	0.48	0.50	0.54	0.56
Dry vegetables	0.01	0.65	0.15	0.00	0.07	0.07	0.05	0.04	0.03	0.03
Meat	1.32	1.77	1.50	3.13	1.51	2.06	2.42	2.92	3.09	2.98
Fish and seafood	0.35	0.27	0.37	0.21	0.36	0.47	0.52	0.62	0.80	0.78
Milk, cheese, eggs	0.39	0.50	0.67	0.72	0.88	1.01	1.16	1.36	1.52	1.88
Wine, beer, cider, etc.	0.06	0.03	0.04	0.08	0.07	0.08	0.06	0.06	0.05	0.04
Total, kg N/capita/year	4.59	6.09	6.10	6.48	5.55	6.13	6.56	7.18	7.60	8.17
gN/capita/day	12.6	16.7	16.7	17.7	15.2	16.8	18.0	19.7	20.8	22.4
Animal feed										
kg N/capita/year	1.7	2.1	1.3	2.3						
gN/capita/day	4.7	5.8	3.7	6.4						
Firewood										
kg N/capita/year	1.46	1.54	0.54	0.24						
gN/capita/day	*4.0*	4.2	1.5	0.6						
Total, kg N/capita/year	7.77	9.76	7.97	9.05	5.55	6.13	6.56	7.18	7.60	8.17
gN/capita/day	21.3	26.8	21.8	24.8	15.2	16.8	18.0	19.7	20.8	22.4

1 stere per capita in the sixteenth century (Woronoff 2002) and 3 steres at the end of the eighteenth century (Rezé 2002; Benoit et al. 2004), before decreasing in proportion to substitution by coal.

Figure 2 reveals the long-term historical trends in the total nitrogen requirements for food, feed, and firewood of Paris during the last three centuries. For the purposes of our study, we will use the figures from the eighteenth century to estimate requirements in the earlier periods which lack direct data, which, as far as food is concerned, are close to the physiological survival diet of 10 g N/cap/day.

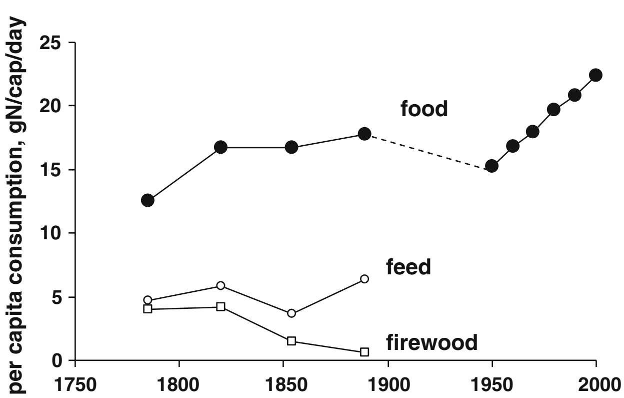

Fig. 2 Per capita food, feed and firewood requirements of Paris city, expressed in terms of nitrogen, estimated (1) from 1785 to 1889 from the data of Paris city toll statistics and (2) from 1950 to 2000 from the data of national French domestic consumption (INSEE 1995)

The potential for commercial export from the rural Parisian basin

The potential for commercial export of agricultural products from a given territory represents the surplus of sustainable agricultural production over the requirements of the rural population. It depends on the technical and social organization of farming activities within the territory and on the capacity of the different components of the landscape mosaic to durably remobilize and return to the fields the amounts of nutrients exported with the crop. As far as nitrogen is concerned and before the advent of the industrial Haber–Bosch process, the latter is mainly dependent on biological N_2 fixation in semi-natural systems.

For example, in slash-and-burn shifting cultivation agriculture, the capacity of the forest during a long fallow period to reconstitute the pool of nutrients exported with the crop from the temporarily cultivated plot is the key to the sustainability of the system. Typically, a farming family of 5 people, with neither mechanical nor animal traction, can exploit a shifting plot of one ha giving a yield of 1,000 kg grain equivalent per ha (18 kg N/ha/year) and just providing the required annual ration of 200 kg grain per capita (Mazoyer and Roudart 1998). With a typical cultivation-fallow cycle of 1/30 years, the sustainable population over the entire territory is 5 inhabitants over 30 ha or about 15 inhab./km^2 (Fig. 3a; Table 3). The system, however, is barely able to release any surplus to be exported outside of the community.

Following the same line of reasoning, the livestock farming agricultural system which prevailed in Europe before the agricultural revolution of the Middle Ages (with slash-and-burn agriculture remaining by places) is characterized by the use of livestock grazing on grassland and to some extent in woodland during the day, to provide manure to arable land during its fallow period, where it spent the night. This allows to raise a cereals crop on the next year with a yield of about 250 kg/ha. This system, typically based on 5 persons farms exploiting 8 ha arable land undergoing biennial rotation, a livestock of 3 cattle units grazing on 18 ha grassland and 5 ha woodland, is able to sustain a rural population of about 16 inhabitant/km^2, without producing any surplus to be commercially exported (Fig. 3b; Table 3).

The agrarian system of the Middle Ages, which emerged in Western Europe as soon as the eighth century and became widespread during the eleventh and twelfth centuries (Contamine et al. 2003) represents from that respect a turning point. It can be similarly described at the level of a representative rural district or ‘finage’ (Benoit et al. 2002). The assumption is made of a community of 300 inhabitants, exploiting an area of 725 ha comprising 300 ha of arable land, 175 ha of grassland and 250 ha of woodland, and raising 100 large livestock units. Animal housing allowed to increase the rate of manure recovery, allowing an input of about 8 kg N/ha/year over the

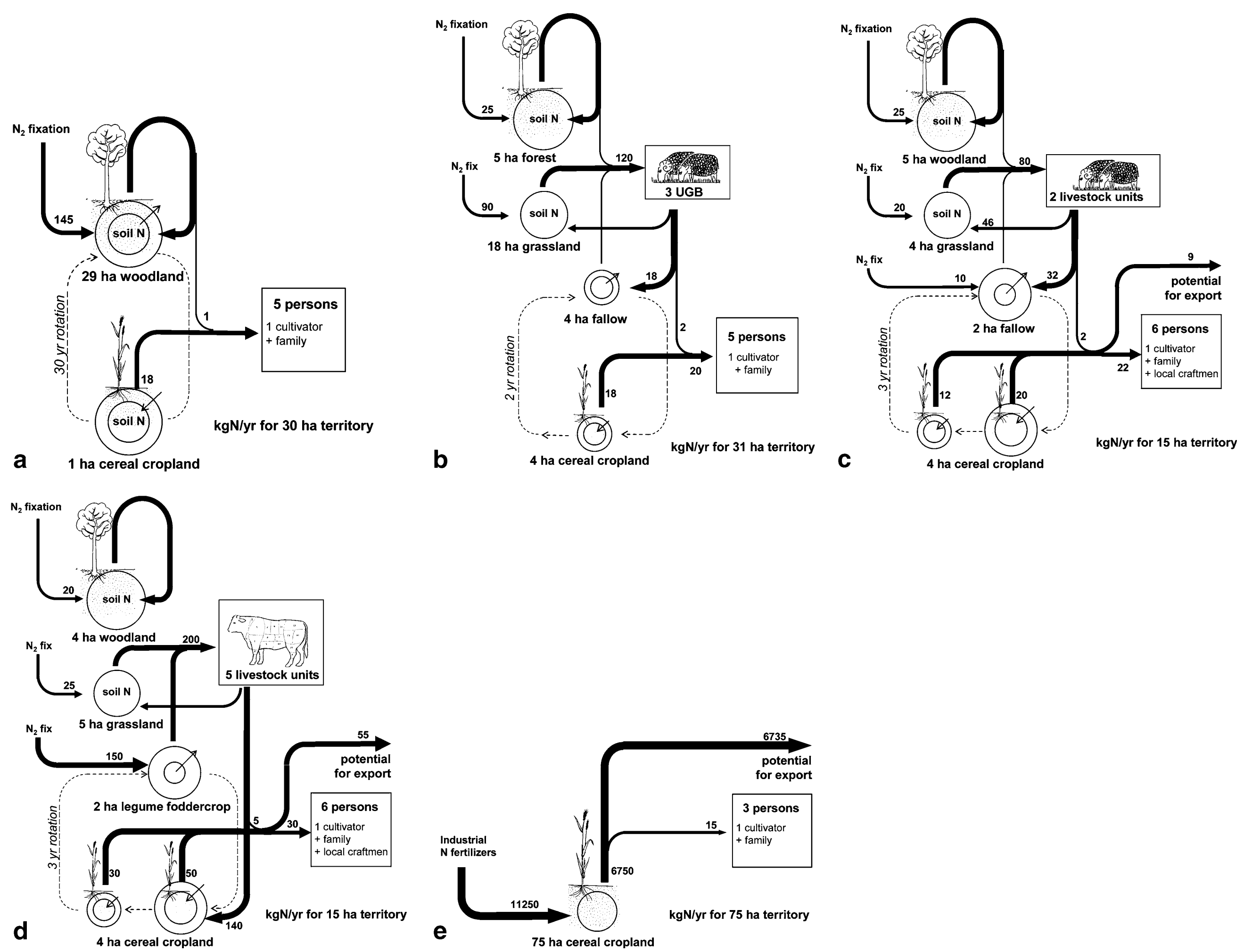

Fig. 3 Description of the nitrogen flows within different western European agrarian systems. The figures are given for a typical family farm (3–6 persons) and the associated land areas. **a**. Slash-and-burn shifting agriculture. **b** Pre-medieval agriculture/cattle farming system based on biennial crop-fallow rotation. **c** Medieval agriculture/cattle farming system based on triennial crop rotation with fallow, as used in small village communities. **d** Nineteenth century agriculture/cattle farming system based on triennial crop rotation with fallow replaced by a N_2 fixing forage crop. **e** Mechanized modern cereal cultivation based on chemical fertilization

Table 3 Functional characteristics of different agrarian systems in Northern France and their potential for commercial nitrogen export. The typical farm characteristics are those proposed by Mazoyer and Roudart (2002)

Agrarian system	Slash-and-burn shifting agriculture	Pre-medieval livestock farming agriculture (biennial rotation with fallow)	Medieval livestock farming agriculture (triennial rotation with fallow)		Eighteenth to nineteenth century livestock farming agriculture (triennial rotation with legume fodder crop)	Modern agriculture with chemical fertilization
			Small farms	Large domains		
Farm characteristics						
Number of persons fed per farm	5	5	6	600	6	3
Number of large cattle unit per farm	–	3	2	650	5	0
Total exploited area per farm (ha)	30	31	16	5,400	15	75
Arable land area per farm (ha)	1	8	6	2,700	6	75
% Arable land as fallow	–	50	33	33	0	0
% Arable land as fodder crop	–	0	0	0	33	0
Associated grassland (ha)		18	3.5	1,450	5	0
Associated woodland (ha)	29	5	5	3,000	4	0
Efficiency of animal dejections reuse (0–1)		0.15	0.4	0.5	0.7	–
Performances						
Fertilisation (kg N/ha arable land/year)	–	4.5	8	7	35	150
Cereal yield (100 kg/ha/year)	10	2.5	4.2	4	11	50
Excedent produced per farm (100 kg/year)	0	0.4	5	5,790	30	3,744
Rural population density (inhab./km^2)	17	16	40	8	40	4
Rural autotrophy (kg N/km^2/year)	60	448	763	540	1,850	8,880
Rural heterotrophy (kg N/km^2/year)	60	446	703	395	1,475	15
Potential for commercial export (kg N/km^2/year)	0	3	60	145	375	8,865
Overall sustainable population (inhab./km^2)	17	17	58	49	145	2,470

The figures for performances, although very close to those given by the latter authors, have been obtained by calculating the farm nitrogen budget, using the following hypothesis: livestock excretion amounts 40 kg N/LCU/year; atmospheric N_2 fixation is 5 kg N/ha/year for grassland, forest and fallow, and 55 in legume fodder crops. For systems before the twentieth century, cereal crop yield (in 100 kg/ha/year) is related to fertilization (fert., kg N/ha/year) according to the hyperbolic relationship: 2000 kg/ha/year × (fert/fert + 30)

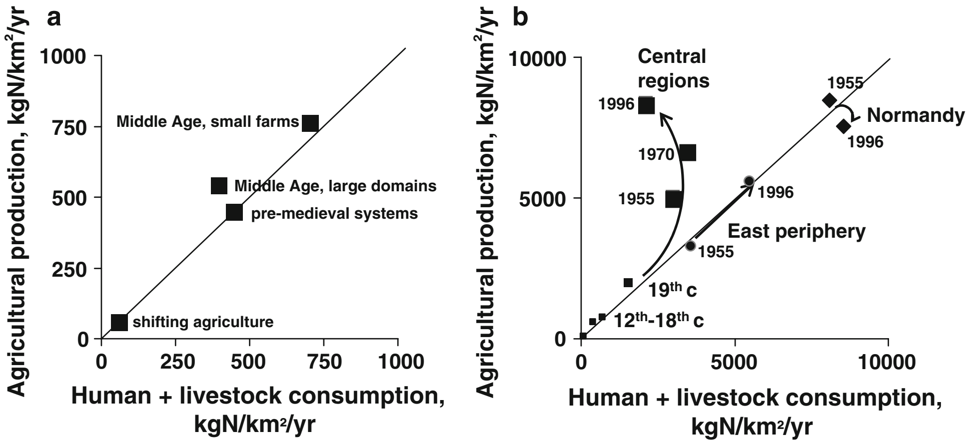

Fig. 4 Autotrophy versus heterotrophy diagram of the agrarian systems of the Paris basin since the tenth century. The total (vegetal) production of agriculture is plotted against the consumption by the local rural population and livestock. Systems located on the diagonal are self-sustaining. Those above the diagonal are autotrophic: their potential for commercial export of N is the difference between production and total local consumption. **a.** Slash-and-burn shifting agriculture; pre-medieval system with biennial rotation; traditional agrarian system of the Middle Ages with triennial rotation; agrarian system of the large monastic or seignorial domains. **b.** Variations in autotrophy versus heterotrophy of the agrarian system of the central and peripheral regions of the Paris basin during the twentieth century. Central regions comprise the French "départements" of Aisne, Marne, Aube, Seine-et-Marne, Eure-et-Loir, Loiret and Yonne. The East periphery comprises the "départements" of Ardennes, Haute-Marne, Meuse and Nièvre. Normandy is here defined as the Orne and Seine-Maritime "départements"

cultivated land area, yielding around 420 kg cereals/ha/year, while the corresponding N export from grassland is easily compensated by the process of atmospheric N_2 fixation at a rate of 5 kg N/ha/year. In this way, not only is the rural population of close to 40 inhab./km^2 fed but a sustainable surplus of about 60 kg N/km^2/year is available for commercial export outside of the community (Fig. 3c; Table 3). Thus, the agrarian system of the Middle Ages is not only more productive than the preceding agricultural systems but it also has a clear autotrophic character, in the sense that agricultural primary production exceeds consumption by the local population and livestock (Le Thi Phuong et al. 2005) (Fig. 4a).

An analysis of the functioning of large ecclesiastical and lay domains in the fifteenth and sixteenth centuries (Benoit et al. 2002) shows that many were organized in a more extensive manner than peasant farms, with a higher animal loading, resulting in a lower human population density (often below 10 inhab./km^2), but a potential for commercial export well over 100 kg N/km^2/year (Table 3). Ironically, these estates created to meet an autarkic ideal, soon evolved towards commercial enterprises, exporting a much larger share of their internal production than the surrounding rural territories, and thus representing more autotrophic systems (Fig. 4a).

Except for certain large ecclesiastical or lay domains, the agrarian system based on a triennial rotation with fallow did not changed significantly in Northern France until the end of the eighteenth century. At that time, a trend emerged in which fallow was replaced by a N_2 fixing fodder crop such as clover, alfalfa, peas or horse beans. This new agrarian system, which did not involved a significant change in either farm size or the structure of the landscape, allowed a considerable increase in livestock density and hence in manure availability and cereal yield (Fig. 3d; Table 3). The potential for commercial export nearly reached 400 kg N/km^2/year, making this agrarian system more autotrophic than any that preceded it.

This system characterized the nineteenth and the first half of the twentieth century. Then, following the discovery of the industrial process of atmospheric nitrogen fixation by Fritz Haber and Carl Bosch in 1910, the transition to modern, mechanized agriculture, based on synthetic fertilizers began. The land area exploited by the average farmer increased by a factor of ten, with a yield per hectare increasing in similar proportion such that worker productivity increased by two orders of magnitude. At the same time, arable farming became entirely liberated from the previously obligatory link with animal husbandry. Depending on geographical or socio-cultural factors, some regions became able to specialize in large-scale crop farming, often exporting most of their production, while others turned to livestock breeding based on massive feed imports. The former is now the current practice in the central Paris basin, where rural territories, now largely devoid of livestock, have become dramatically autotrophic, with commercial export potentials of over 5,000 kg N/km^2/year (Table 3; Figs. 3e, 4b). In contrast, the peripheral areas of the Paris basin turned to cattle breeding and fell in heterotrophy (see also Billen et al. 2007a; Mignolet et al. 2007).

The 'food-print' of Paris city

By equating the food, feed, and firewood requirements of Paris to the potential for commercial export of agricultural products from the rural territory surrounding the city, we can estimate the area of the territory required to meet this urban demand. This area defines the extent of the imprint exerted by the city on the rural agricultural systems. Contrary to the concept of the 'ecological foot-print' as defined by Wakernagel and Rees (1996), our 'food-print' indicator only takes into account the area required for producing agricultural goods, and is expressed in terms of the effective surface of the surrounding territory, instead of using a normalized global-area unit.

Using (1) the Paris population sizes of Fig. 1, (2) the per capita N requirements of Table 2, and (3) the potential for commercial export estimated in Table 3, the area of rural territory theoretically required to supply the city can be calculated (Fig. 5). Aside from the two demographic decrease periods of Paris in the fourteenth and sixteenth centuries, the results show an underlying increasing trend until the eighteenth century when the area reached around 60,000 km^2; a value which corresponds to the size of the Seine watershed. This increase, however, is modest with respect to that of the urban population (Fig. 1). Despite a 50-fold increase in the population of Paris since the fifteenth century, the food-print of the city barely increased twofold. In contrast, the further doubling of the population in the twentieth century was paradoxically accompanied by a fivefold decrease in the food-print.

Our theoretical estimation for the area at the end of the eighteenth century can be validated by the results of the detailed analysis of Abad (2002). The author stresses that as early as the middle of the eighteenth century, the Parisian food market acted as very significant factor in the redistribution of financial resources throughout the entire kingdom but, despite this, the city imported most of its food from the adjacent provinces (Table 4) when these were expressed in nitrogen units. This represents a total area close to 60,000 km^2. Most cereal products were obtained from the provinces of Ile-de-France, Brie-Champagne and Orléanais, most meat was derived from Normandy, Ile-de-France and Limousin and firewood was imported mainly through floating from the remote Morvan area in Bourgogne (Boissière 1991; Bruley 1995; Benoit et al. 2002, 2004) (Fig. 6). A clear specialization of these regions is thus already obvious in the nature of the commercially exported agricultural products, evoking, although in an octopus-like version, the concentric areas of von Thünen' model (1826). For those provinces that contributed most significantly, the calculated area-specific rate of N export, ranging from 10 to 97 kg N/km^2/year (Table 4), is remarkably similar to our theoretical estimate of 60–150 kg N/km^2/year at that time, particularly when it is considered that the export of these provinces was not only, even if mainly, destined to Paris. This is probably especially true for Picardie which exported its cereals to Flanders and beyond.

The recent and spectacular decrease in the Parisian food-print observed since 1950 (Fig. 5) is another striking result provided by our analysis. The yields of modern agriculture as practised in the central regions of the Paris basin, often reaching 10,000 kg cereals/ha/year, are so high that they largely exceed the needs of Paris and are exported elsewhere, sometimes over very large distances. Table 5 illustrates this point by comparing the present urban food consumption, deduced from the data of Table 2 and the total population of the Paris conurbation, with the agricultural production of the rural areas of the Seine watershed, considered as the 'historical' supplying territory of Paris. Regarding most agricultural goods with the exception of meat and seafood, the Parisian basin produces

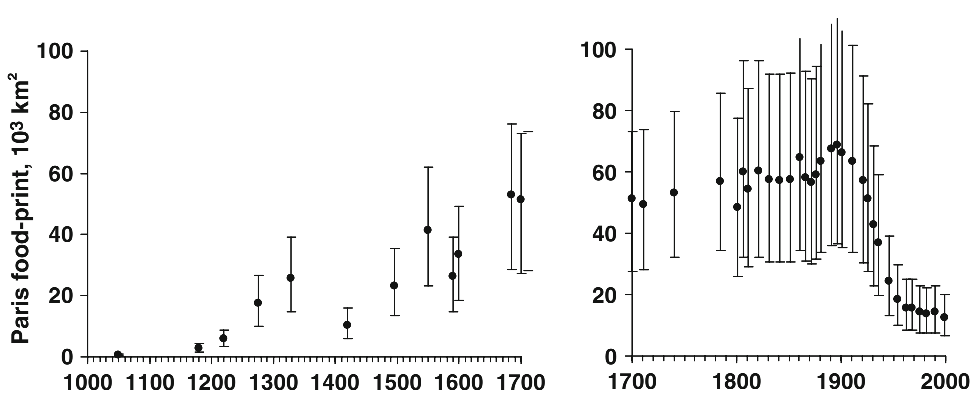

Fig. 5 The theoretical estimate of the area required to supply the food, feed and firewood requirements of Paris city during the last millennium. The area is obtained by dividing the N requirement of Paris (Fig. 1; Table 2) by the estimate of the potential for commercial export of N by the rural territory at the same period (Table 3). *Error bars* indicate the minimum and maximum estimates, given the uncertainty on per capita N requirement, and on the potential for commercial export from the rural area

Table 4 Origin by provinces of the main food, feed and firewood products (pdcts) imported to Paris at the end of the eighteenth century (from Abad 2002; Bruley 1995; Boissière 1991)

	Consumed in Paris	Imported from																
		Ile de France	Normandie	Brie Champagne	Orléanais	Picardie-Boulonnais	Bourgogne	Berry	Maine	Nivernais	Marche-Limousin	Flandres-Artois	Franche Comté	Anjou-Tourraine	Poitou	Bretagne	Other provinces	Out of France
Area, km^2 254,022		18,504	29,244	36,029	19,665	14,259	28,591	14,477	15,239	16,472	17,778	10,086	17,379	16,146		23,874	37,117	
Human food, ton N/year																		
Bread and cereals	1,470	924	29	332	101	58	0	0	0	0	0	0	0	0	0	0		31
Vegetables and fruits	130	117	5	4	1	0	0	0	0	0	0	0	0	0	0	0		0
Meat	857	98	344	42	47	12	1	58	28	26	132	7	0	21	14	2		0
Fish and seafood	231	3	115	20	14	17	11	2	0	7	0	1	0	0	4	11		24
Milk. cheese. eggs, etc.	252	15	25	32	10	9	0	0	0	0	0	10	15	0	0	0		25
Wine, beer, cider, etc.	38	6	0	4	4	0	7	0	0	0	0	1	0	1	0	0		0
Total man food, tonN/year	2,982	1,163	518	434	177	96	19	60	28	33	132	19	15	22	18	13	26	79
Animal feed, tonN/year	1,119	626	269	312	95	54	0	0	0	0	0	0	0	0	0	0	0	0
Firewood, tonN/year	948	0	0	66	0	0	881	0	0	0	0	0	0	0	0	0	0	0
Total, ton N/year	5,048	1,788	788	812	272	150	900	60	28	33	132	19	15	22	18	13	26	79
% of Paris supply	100	35	16	16	5	3	18	1	1	1	3	0	0	0	0	0	1	2
Export, kg $N/km^2/year$[a]		97	27	23	14	11	31	4	2	2	7	2	1	1	1	0.4		
As vegetal pdcts		90.4	10.4	18.1	10.2	7.9	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0		
As animal pdcts		6.3	16.6	2.6	3.6	2.7	0.4	4.2	1.9	2.0	7.4	1.8	0.9	1.3	0.7	0.4		
As firewood		0.0	0.0	1.8	0.0	0.0	30.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		

[a] Area-specific rate of N exported to Paris (kg $N/km^2/year$)

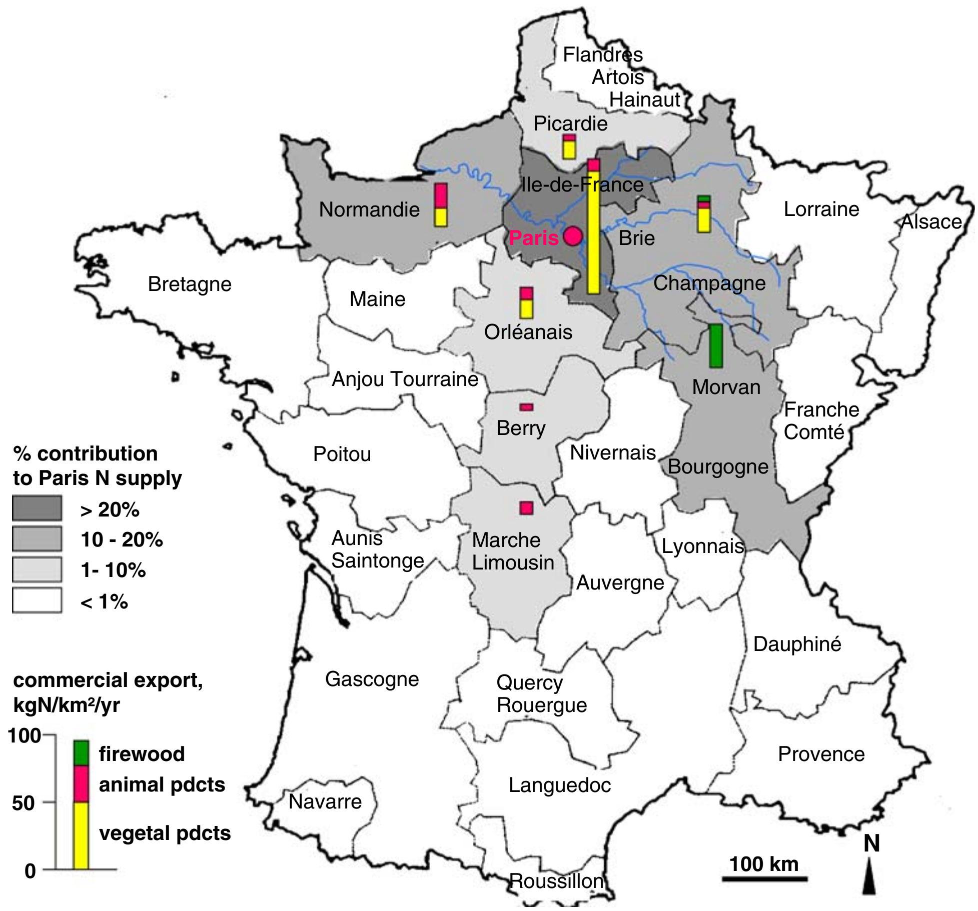

Fig. 6 **a** Contribution of the various provinces to the supply of food, feed and firewood to Paris at the end of the eighteenth century [calculated from the figures of Abad (2002) for food and feed and of Bruley (1995) for firewood]. **b** Area-specific rate of commercial export of agricultural products from the provinces (in kg N/km^2/year)

Table 5 Present (2000) consumption of agricultural goods by Paris conurbation (9,650,000 inhabitants) and corresponding production by the rural areas of the Seine watershed, expressed in terms of their nitrogen content (to be compared with Table 4, note that units here are ktonN/year)

	Consumed in Paris conurbation	Production from		
		Central Paris basin[a]	Normandy[b]	Eastern belt[c]
Area, km^2		52,657	17,929	18,257
Human food, ktonN/year				
Bread and cereals	13	263	43	39
Vegetables and fruits	11	342	37	26
Meat	29	7	7	3
Fish and seafood	8	–	–	–
Milk, cheese, eggs, etc.	18	7	9.68	2.85
Total, kton N/year	78	619	96	72
% of Paris supply	100	789	123	92
Potential export, kg N/km^2/year		11,597	5,155	3,209
As vegetal pdcts		11,401	4,350	2,914
As animal pdcts		196	805	295

[a] Seine et Marne, Oise, Aisne, Marne, Aube, Yonne, Eure, Eure et Loir

[b] Orne, Calvados, Seine Maritime

[c] Ardennes, Haute Marne, Nièvre

much more than is required to feed the city. On the other hand, examination of the available freight statistics for the Ile-de-France region (DREIF 2003) shows that, of the 14,000,000 tons of agricultural goods entering the Paris conurbation by road, rail or waterway annually, more than 75% of which is derived from outside of the Seine watershed, as much as two-thirds are re-exported after processing (Barles 2007). It is therefore very difficult to assess the origin of the products internally consumed by the city, but it highlights that the present food market of Paris is extremely open and only loosely dependent upon products from the immediately surrounding regions.

Conclusions

The data gathered in this paper describe how the growth of the food requirements of Paris over one millennium have kept pace with the development of the commercial export potential of the surrounding rural territory. They show how closely the city and its hinterland have been linked together until the last 50 years. Paris developed at the confluence of the three major tributaries of the Seine River, at the centre of the watershed and in the middle of a large and fertile sedimentary basin. This territory constituted the natural hinterland of the city, from which it could obtain and transport within the walls most of the agricultural resources needed for its development during a period extending over more than the first nine centuries of the last millennium. On the other hand, in response to the growing urban demand, the rural areas evolved to focus on exportation and became specialized agrarian systems, making possible the development of Paris without the excessive extension of its supplying area, which remained largely contained within an area roughly corresponding to the Seine Basin. Clearly in this example, the long-term process of urbanization consisted of a mutual evolution of the rural and urban territories in their management of biogeochemical fluxes.

Only during the last 50 years has this close interaction apparently been disrupted. Due to the unprecedented increase in agricultural yields made possible by the general uptake of modern farming techniques, Paris ceased to constitute the main outlet for the agricultural products from the Paris basin. Currently, agriculture in this area is mostly driven by the logics of international markets rather by local urban demand, which today represents only one of many destinations for the agricultural products of the region. Conversely, the modern agrarian system now dominating the Parisian basin is extremely demanding in external resources such as fuel, chemical fertilizers and pesticides, and generates environmental dysfunctions in the form of water and, to a lesser extent, air pollution (ref. in Billen et al. 2007b). The increasing pressure placed on the rural territory for environmental resources other than space itself is not taken into account in our spatial assessment of the impact of Paris food requirements as defined here. This should be kept in mind when interpreting the calculated reduction in the food-print during the last 50 years (Fig. 5).

Indeed, contrary to the ecological footprint proposed by Wakernagel and Rees (1996), our spatial imprint calculation refers to the acreage of a "real" rural territory theoretically required to supply the food of a city with the current farming techniques. It does not consider a comprehensive account of all resources required, such as energy, fertilizers and waste disposal, converted into abstract and additive "global hectare equivalent" units. Although both approaches may be useful and complementary, we defend the idea that a closer look at how rural territories evolve in terms of their capacity for commercial export of nitrogen containing food products in response to the demand from local or distant urban markets might be a promising approach to understand the global issue of world food resource allocation in the context of increasing population sizes and urbanization.

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