The Seine Watershed Water-Agro-Food System: Long-Term Trajectories of C, N and P Metabolism

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Contents

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Abstract Based on the GRAFS method of biogeochemical accounting for nitrogen (N), phosphorus (P) and carbon (C) fluxes through crop, grassland, livestock and human consumption, a full description of the structure and main functioning features of the French agro-food system was obtained from 1850 to the present at the scale of 33 agricultural regions. For the period since 1970, this description was compared with the results of an agronomic reconstitution of the cropping systems of the Seine watershed based on agricultural census and detailed enquiries about farming practices at the scale of small agricultural regions (the ARSeine database), which were then used as input to an agronomical model (STICS) calculating yields, and the dynamics of N and C. STICS was then coupled with a hydrogeological model (MODCOU), so that the entire modelling chain can thus highlight the high temporal inertia of both soil organic matter pool and aquifers. GRAFS and ARSeine revealed that the agriculture of the North of France is currently characterised by a high degree of territorial openness, specialisation and disconnection between crop and livestock farming, food consumption and production. This situation is the result of a historical trajectory starting in the middle of the nineteenth century, when agricultural systems based on mixed crop and livestock farming with a high level of autonomy were dominant. The major transition occurred only after World War II and the implementation of the Common Agricultural Policy and led, within only a few decades, to a situation where industrial fertilisers largely replaced manure and where livestock farming activities were concentrated either in the Eastern margins of the watershed in residual mixed farming areas or in specialised animal production zones of the Great West. A second turning point occurred around the 1990s when regulatory measures were taken to partly correct the environmental damage caused by the preceding regime, yet without in-depth change of its logic of specialisation and intensification. Agricultural soil biogeochemistry (C sequestration, nitrate losses, P accumulation, etc.) responds, with a long delay, to these long-term structural changes. The same is true for the hydrosystem and most of its different compartments (vadose zone, aquifers, riparian zones), so that the relationship between the diffuse sources of nutrients (or pesticides) and the agricultural practices is not immediate and is strongly influenced by legacies from the past structure and practices of the agricultural system. This has strong implications regarding the possible futures of the Seine basin agriculture.

Keywords Agriculture, Aquifers, Carbon, Denitrification, Fertilisers, Greenhouse gases, Leaching, Nitrogen, Nutrients, Phosphorus, Riparian wetlands, Soil

1 Introduction

Given that it deeply affects the functioning of terrestrial ecosystems, agriculture is not only the major determinant of landscape structure, biodiversity and soil biogeochemistry but also an essential factor in determining the hydrology and water quality of river systems and their receiving marine coastal waters. In particular, the nutrient (C, N, P, Si) composition of ground- and surface water is largely dependent on diffuse sources from the watershed which respond to land use and agricultural practices. This response, however, is far from being simple and direct, due to the complex cascade of processes, including storage and elimination, that nutrients, emitted from the root zone of cropping systems, have to move across, with temporalities ranging from sub-hourly to multi-decadal.

The Seine watershed, with a catchment area of about 70,000 km^2, is entirely located within one of the most fertile areas of Western Europe, the Paris Basin. This geological unit consists of concentric tertiary sedimentary formations (alternating clay, sandstone and limestone), covered by loess in its central part and lying on a basement of ancient crystalline rock formations outcropping at the extreme South-East and North-East (Fig. 1a). Paris developed in the middle of the drainage network, at the convergence area of large tributaries draining this basin, which historically was a favourable factor in terms of the city's food, feed and fuel supply. Currently, the central zone of the Seine watershed, around the huge Paris conurbation, is oriented towards mass production of cereals and industrial crops, while animal breeding is restricted to the peripheral areas of the basin where pedoclimatic conditions are less suitable to stockless cropping systems (Fig. 1b).

The Seine River basin has been subject to intensive research for 30 years within the PIREN-Seine programme [2, 3]. Here we present a synthesis of this work, addressing the interrelated issues of agricultural dynamics, soil biogeochemistry as well as ground- and surface water nutrient contamination. The purpose of this chapter is to describe, over a 150-year period, the long-term dynamics through which the current state of the agricultural system has gradually been constructed, in order to understand both the drivers of change and the inertia of the different environmental compartments of the water-agro-food system of the Seine watershed. Based on this long-term view of the role of legacies on the current system functioning, the issue of its possible future evolution will be shortly addressed.

2 Material and Methods

This chapter is mainly based on the results of two complementary integrated research efforts developed in the PIREN-Seine programme (www.piren-seine.fr), namely, the GRAFS-Riverstrahler and the ARSeine-STICS-MODCOU approaches, which are here compared and merged for the very first time. These two approaches differ in their level of detail, time and space resolution and the duration of the historical period they are able to encompass.

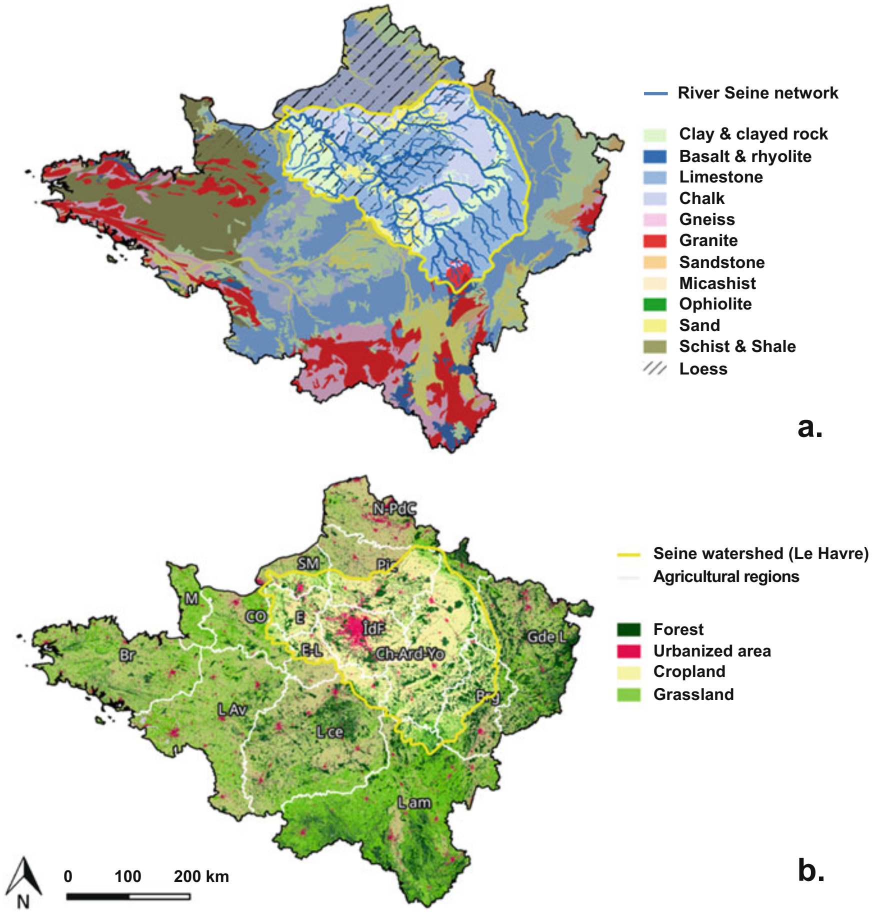

Fig. 1 The Seine basin within in its wider geographical context. (**a**) The Seine drainage network and the lithological zones within and around the Paris Basin (source: BRGM www.brgm.fr). (**b**) Land use (source: Corine Land Cover 2012, www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france) and agricultural regions defined by Le Noë et al. [1]. *NPdC* Nord-Pas-de-Calais, *Pic* Picardy, *SM* Seine Maritime, *M* Manche, *CO* Calvados-Orne, *E* Eure, *E-L* Eure-et-Loir, *IdF* Île-de-France, *Ch-Ard-Yo* Champagne-Ardenne-Yonne, *GdeL* Grande Lorraine, *Brg* Burgundy, *Br* Brittany, *L Av* Loire Aval, *Lce* Loire centrale, *L am* Loire Amont

GRAFS (for Generalized Representation of the Agro-Food System) is a biogeochemical accounting tool for describing the N, P and C fluxes across the crop- and grassland, livestock and human population of a given territory [4]. It is conceived as a framework for analysing the functioning of agricultural systems, their requirements in terms of resources and their environmental losses, as well as their long-term trajectories, since 1850 [5], based on data mostly derived from the compilation of official agricultural statistics available at the *département* scale (typically 6,000 km^2). It provides the required data for running the Riverstrahler model [6, 7] (www.fire.upmc.fr/rive), which calculates the nutrient transfers and the ecological functioning of each tributary of the river system, given the diffuse and point sources of nutrient and organic matter from the watershed. The calculated nutrient fluxes at the outlet of the river system can then be used by a coastal marine model such as ECO-MARS 3D to assess the eutrophication generated by these fluxes [8–11].

The ARSeine database [12] offers a spatially detailed and distributed description of the Seine-Normandie cropping systems over the 1970–2015 period, including land use, crop rotations and detailed management techniques at the *Petites Régions Agricoles* scale (typically 1,000 km^2). It has been designed to provide the inputs to a 2D-distributed version [13] of the STICS model [14–18]. STICS is an agronomical crop model simulating crop production and the components of the N cycle at the same space and time resolution. Input soil parameters have been defined for each soil unit of the Soil Geographic Database of France at the 1:1,000,000 scale [19], using local pedotransfer functions [20]. Daily values of nitrate leaching predicted by STICS are used as an input to the hydrogeological MODCOU model [21], which calculates the recharge and nitrate contamination of the basin's main aquifer formations [13, 22].

Evaluating the uncertainty on the results of such long-term reconstruction of environmental data is a critical task. As far as modelling approaches are concerned, two types of uncertainty can be distinguished: structural uncertainties related to the adequacy of the model's representation of the system and operational uncertainties related to the accuracy in the data and parameters used [23]. The latter can be evaluated using Monte Carlo methods to assess how uncertainty on the raw data propagates to final model results; this approach shows typical uncertainties of approximately 25% for the GRAFS approach [4]. Structural uncertainties are by essence much more difficult to assess. They have been roughly estimated at 15% for the STICS model [20].

3 Trajectory and Biogeochemical Functioning of the Agricultural System

3.1 Long-Term Changes in the Structure of the Northern France Agricultural System

Until the beginning of the twentieth century, mixed crop and livestock farming systems dominated everywhere in France (Fig. 2a). Manure and symbiotic N fixation by grassland and legume crops inserted in rotations were the only sources of cropland fertilisation. Specialisation into stockless cropping systems, relying on

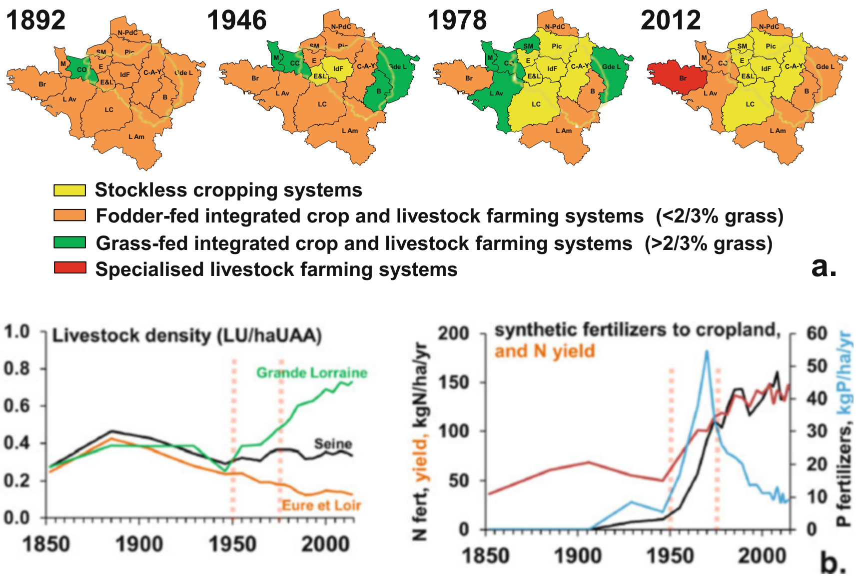

Fig. 2 (**a**) Gradual specialisation of agricultural systems in the North of France from 1850 to 2015. (**b**) Long-term variation of number of livestock density (in livestock units per ha of agricultural land) (right), N (black curve) and P (blue curve) fertilisation and crop yield (right) in the Seine basin (after [5]) (Three periods from 1850 to 1950, from 1950 to 1975 and from 1975 to 2015 can be distinguished)

industrial N and P fertilisers, is developed first in the Île-de-France and Eure-et-Loir regions in the first half of the twentieth century, owing to the proximity of Paris and transport infrastructures. After World War II, a voluntarist state policy of agriculture modernisation led to increased farm size, the rural exodus, the rapid increase of industrial fertiliser use and regional specialisation [24, 25] into either stockless cropping systems (dominating in the middle of the Paris Basin) or intensive livestock farming systems (in the Great West), often highly dependent on the import of feed (Fig. 2a). This resulted in an unprecedented opening of the nutrient cycles, with increasing environmental losses and growing insertion into international markets. After the 1980s, public policies shifted from interventionist support in favour of increasing production to give way to greater liberalism. However, since the 1990s, the rise of fertiliser prices together with the implementation of agro-environmental measures to limit nutrient losses resulted in an inversion in the trends of mineral fertilisation. N and P soil balances decreased, even becoming negative in the case of P in arable soils (Figs. 2b and 10a). These changes are clearly reflected in the patterns of N fluxes between arable land, permanent grassland, livestock and human nutrition (Fig. 3); similar trends are also apparent in terms of P and C fluxes [4, 5].

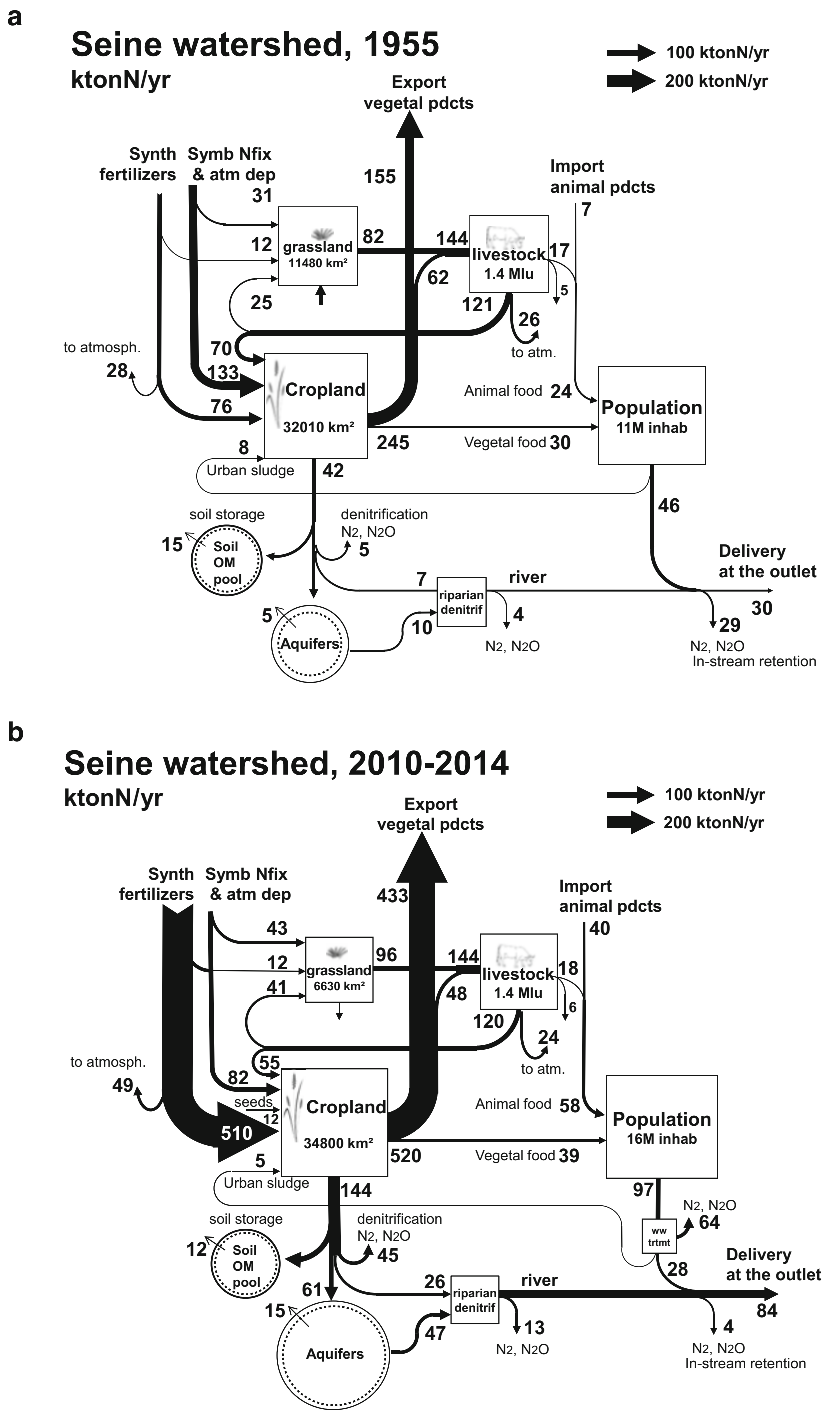

Fig. 3 GRAFS representation of N fluxes between cropland, grassland, livestock, human population and the hydrosystem in the Seine basin around (**a**) 1955 and (**b**) 2010–2014. (approximated fluxes in thousand metric tons of N)

3.2 Changes in Land Use and Crop Rotations

At a finer scale, the changes in land use and agricultural practices have been documented since the 1970s (the ARSeine database [12]). The specialisation in a stockless cropping system in the centre of the watershed went together with a strong reduction of permanent grassland surfaces (Fig. 4a), which are now restricted to the Eastern and Western fringes of the basin.

A significant reduction of the length and diversity of arable crop rotations has also occurred during the same period. Grain and forage legumes, which were basic components of crop rotations in the middle of the twentieth-century agriculture, were abandoned in many places (Fig. 4a). A sharp drop in the frequency of spring crops (Fig. 4b), such as spring barley and grain maize, is also observed, while rapeseed has gained ground.

3.3 Yield-Fertilisation Relationship

While the variations of crop productivity during the second half of the nineteenth century closely followed those of livestock density and the resulting availability of manure, the rapid yield rise observed after 1950 is the direct consequence of the increased use of mineral fertilisers (Fig. 2b). The historical trajectory followed until 1980 by agriculture in terms of crop yield (Y, in kgN/ha/year) and total N inputs to the soil (F, in kgN/ha/year) (through manure, synthetic fertilisers, symbiotic N fixation and atmospheric deposition) followed a hyperbolic curve reflecting the non-linear agronomical relationship between yield and fertilisation [26] (Fig. 5a) expressed as

$$Y = Y\max \cdot F/(F + Y\max)$$

where Ymax is a parameter representing the maximum yield at saturating fertilisation.

After 1980, owing to improvements in agronomic practices, a shift occurred towards another trajectory with higher yields, in spite of lower fertilisation rates in the most recent period. The new trajectory is coherent with the yield-fertilisation relationship observed, although with considerable variability, for individual crop rotation systems, in both conventional and organic farming systems (Fig. 5b). It is remarkable that no significant difference in the yield-fertilisation relationship, expressed in total protein production over the whole crop rotation, is apparent between organic and conventional systems of the same pedoclimatic contexts, contrary to the common opinion that organic systems would be intrinsically less productive.

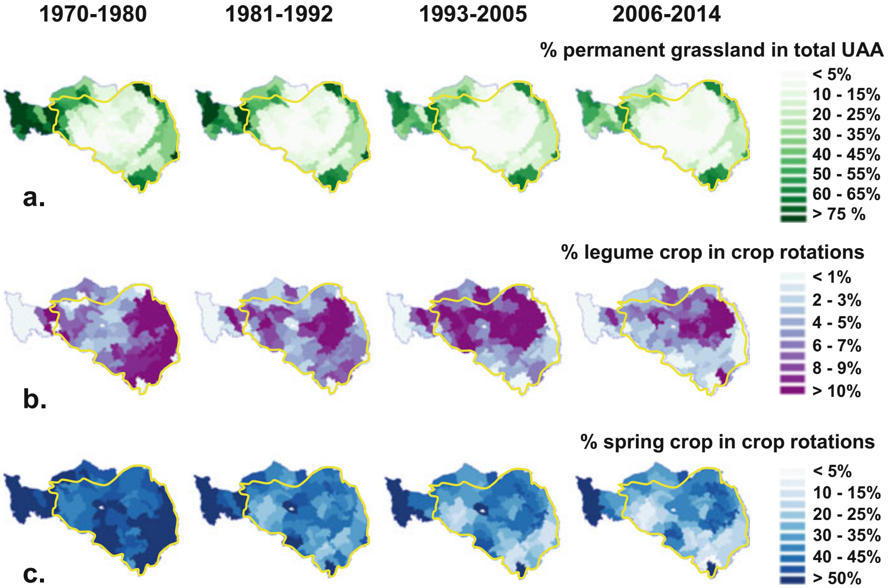

Fig. 4 Long-term changes in the frequency of (**a**) permanent grassland (in % of usable agricultural area), (**b**) legume crops, (**c**) spring crops (in % of crop rotation), during the 1970–2014 period. The limits of the Seine watershed are shown as a fine yellow line

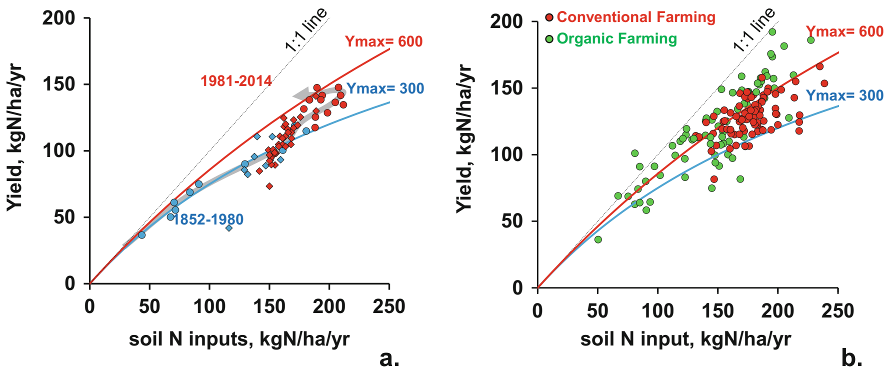

Fig. 5 (**a**) Long-term trajectory of cropland yield and soil N inputs averaged over the Seine watershed, as revealed by the GRAFS analysis for 1852–2014 (circles) [5] and by the application of the STICS model to the crop rotation and technical itinerary (diamonds) [13, 22] reconstituted in the ARSeine database. Until 1980 (blue symbols), the trajectory follows a single hyperbolic curve with the *Y*max parameter close to 300 kgN/ha/year, while a shift to a higher curve is observed for the more recent period (red symbols). (**b**) Yield vs soil N input relationships for current conventional (red points) and organic (green points) farming crop rotation. Data from documented crop rotations gathered by Anglade et al. [27, 28] and Rakotovololona et al. [29]

4 Soil Biogeochemistry Reflects This Trajectory

Because of the large size of these element pools, C, N and P metabolism in cropland soil is largely affected by the long-term structural changes in the agro-food system and agricultural practices described in the previous section.

4.1 Soil Organic Carbon Storage

Organic C storage in agricultural soil is determined by the balance between (1) humified organic C inputs from above- and below-ground crop residues and manure application and (2) soil organic matter mineralisation depending on the soil content of labile organic matter and pedoclimatic properties [30]. C sequestration in agricultural soil therefore always reflects a long-term temporary imbalance between C inputs to soil, which are determined by agricultural practices and soil C mineralisation [31]. The dynamics of organic C storage in crop and grassland soils of the Seine basin over the 1850–2015 period was calculated through the application of the AMG model [32, 33], using the GRAFS estimation of humified C inputs [30] (Fig. 6a, b). A low rate of C sequestration occurred during the second half of the nineteenth century, followed by a destocking period until 1950 (Fig. 6c). Then a period of enhanced C sequestration occurred during the phase of rapid modernisation of the basin's agriculture, due to increased net primary production, and associated underground residue inputs, counterbalancing the reduction in manure inputs in the regions adopting stockless cropping systems. The mean rate of C sequestration then gradually levelled off and is now close to 40 kgC/ha/year, i.e. about 1‰ of the Corg stock in the top 30-cm top of soil. However, in the North-Western regions of France, destocking of organic C in cropland soil occurs (Fig. 6d). These results are consistent with the predictions of the STICS model concerning the variations of soil organic nitrogen (SON), which are strongly linked with those of soil organic carbon (SOC) in arable crops (Fig. 6e). The current agriculture in France is therefore far away from the objective assigned by the COP21 of an annual 4‰ increase in soil organic C content to counterbalance anthropogenic CO_2 emissions and mitigate climate change (the so-called 4‰ initiative; http://www.4p1000.org/ [34]). This is reinforced by the fact that total agricultural area has significantly decreased in the same period, at a rate comparable to that of organic C storage.

4.2 Agricultural Greenhouse Gas Emissions

Besides C emissions related to a possible negative C soil balance, greenhouse gas (GHG) emissions by the agricultural sector include N_2O emissions linked to nitrification and denitrification in cropland and grassland soils, CH_4 emissions mostly related

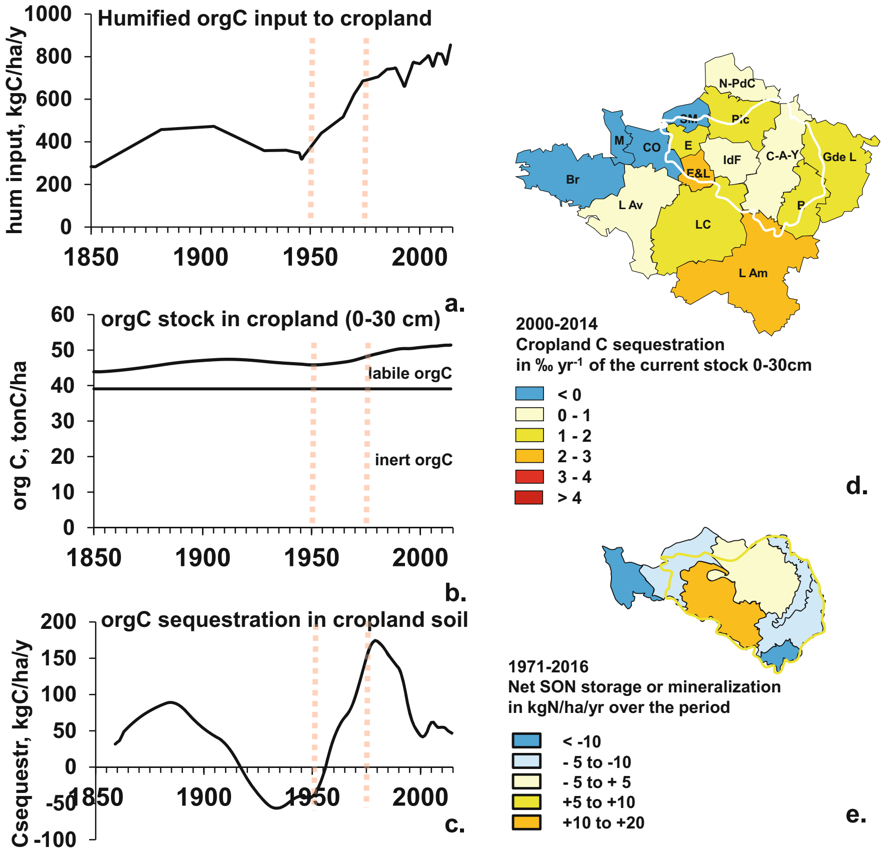

Fig. 6 (**a**) Long-term trends of humified organic carbon inputs to cropland soil of the Seine basin. (**b**) Calculated evolution of the labile and inert C stock in the 30-cm top soil of cropland. (**c**) Rate of C sequestration in kgC/ha/year and (**d**) in ‰ year^{-1} of the total stock in the 30-cm top soil of cropland (data from [30]). (**e**) Distribution of SON storage per agricultural district simulated by STICS in arable land from 1971 to 2013 [20]

to enteric fermentation of livestock and manure management as well as CO_2 emissions linked to fossil fuel consumption for mechanisation, heating, transport of feed and fertiliser manufacture. These components of the GHG balance were estimated by Garnier et al. [35] for the Seine basin agriculture over the 1852–2015 period. Soil N_2O emissions were estimated from an empirical relationship with exogenous N inputs (as synthetic fertilisers and manure), rainfall and temperature (Fig. 7a). They fit well with the predictions of the STICS model in agricultural zones [13]. CH_4 emissions from ruminants and monogastrics were estimated using livestock numbers and time-dependent emissions factors. CO_2 emissions were calculated following the ClimAgri methodology [36]. While CH_4 emissions did not change much over the period under study in the Seine basin, owing to the gradual reduction of

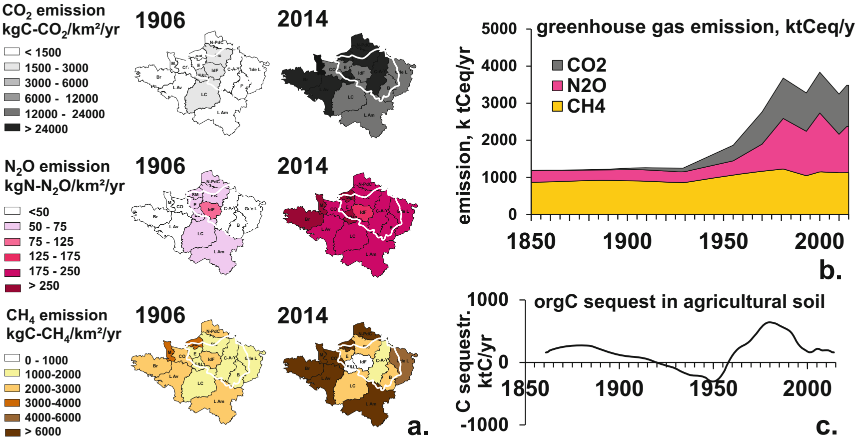

Fig. 7 GHG emissions from the agricultural sector of the Seine basin. (**a**) Geographical distribution of CO_2 emissions from fuel combustion (kg C-CO_2/km^2/year), N_2O emissions from cropland and grassland (kg N-N_2O/km^2/year) and CH_4 emissions by livestock (kg C-CH_4/km^2/year) in the Seine basin in 1906 and 2014. (**b**) Long-term variation of agricultural greenhouse gas emissions from the Seine basin expressed in C-CO_2 equivalent (ktonC-CO_2equ/year) (after [35]). (**c**) Long-term C sequestration in crop soils [30]

livestock farming activity from the greatest part of the territory (Fig. 2b), N_2O and direct CO_2 emissions increased by more than a factor of 4 during the post-World War II period and then levelled off after the 1980s (Fig. 7b). When expressed in terms of equivalent C emissions, the current level of GHG emissions by agriculture in the Seine basin is about 3,400 ktonC-CO_2 eq/year. This is one order of magnitude higher than the current C sequestration rate into the organic matter pool of agricultural soils (180 ktonC-CO_2/year, [30]), as well as the maximum sequestration rate ever reached over the 1850–2015 period (Fig. 7c), showing that the 4‰ initiative, although desirable in terms of improvement of the soil quality, cannot be considered as a very significant climate change mitigation strategy, at least for France.

4.3 *Nitrogen Soil Storage and Leaching*

The balance of N inputs to cropland soils (as manure, fertilisers, symbiotic fixation and atmospheric deposition) and N export through harvest represents the potential N losses to the atmosphere (mostly as denitrification and ammonia volatilisation) or the hydrosphere (as nitrate leaching) (Fig. 3). Part of this balance is retained, however, within the organic N pool of the soil, depending on both the nature on the N inputs and the pedoclimatic conditions. As the C:N ratio of the soil organic matter does not deviate much from a mean value of 10 gC/gN, the above estimate of the C sequestration rate (Fig. 7c) can be used to calculate the long-term storage of N in

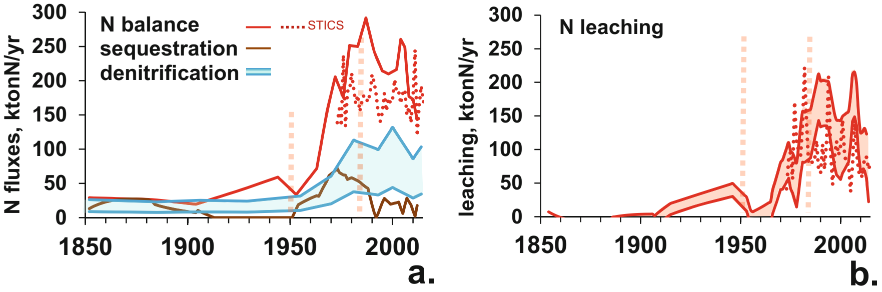

Fig. 8 (**a**) N balance of agricultural soils estimated from the GRAFS approach over the 1852–2015 period and its breakdown in terms of N storage and denitrification. The dotted red line is the estimation of N balance according to the coupled ARSeine database/STICS model. (**b**) N leaching calculated as the difference between N balance and N storage and denitrification. The dotted red line represents the N leaching calculated by the STICS model during the 1970–2015 period

organic form (Fig. 8a). We have no direct estimate of N loss through soil denitrification, which is very difficult to measure and to model. However, the estimate of N_2O emissions (Fig. 7) can be used to calculate a range of denitrification rates (Fig. 8a), assuming that the average N_2O/N_2 ratio lies between 10 and 30% [37–40]. Leaching is the remaining part, as shown in Fig. 8b.

The application of the STICS model at the scale of the Seine basin since 1970 allows a direct estimation of N leaching (Fig. 8b). These values match reasonably well with the estimation by difference between N balance, soil N storage and denitrification (Fig. 8b). The distribution of N surplus between N storage, denitrification and leaching during the last two decades (8–10%, 15–55%, 35–75%, respectively) is consistent with similar budgets experimentally established in long-term agronomical experiments in the Paris Basin [29, 31, 41].

4.4 *Phosphorus Dynamics and Erosion*

Contrasting with the high environmental mobility of N, P, once applied to soils in excess over the requirements of crop growth, accumulates within the soil where it remains strongly adsorbed. The only significant loss mechanism is net erosion, which mostly affects cropland. It has been estimated at 0.6 t soil/ha/year for the Seine basin based on the data calculated by Borelli et al. [42]. This represents a net erosion loss rate of about 0.00015 year^{-1} for the cropland soils of the Seine basin when expressed relative to the soil mass in the 0 to 30-cm layer.

Using this estimate, the long-term P balance of cropland (Fig. 9a) can be used to calculate the storage of this element in the soil pool (Fig. 9b). While P stocks decreased during the 1850–1950 period, due to a low fertilisation rate, a sharp increase is observed during the 1950–1980 period, characterised by considerable overfertilisation. For the past 30 years, P fertilisation levels have considerably

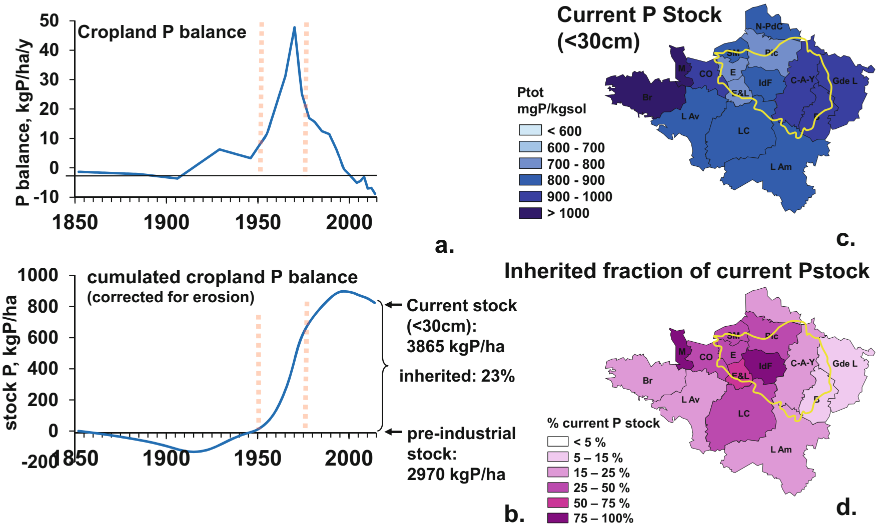

Fig. 9 (**a**) P balance of cropland soils of the Seine watershed estimated from the GRAFS approach over the 1852–2015 period. (**b**) Accumulation of P in cropland soil estimated from the cumulated P balance corrected for net erosion losses. (**c**) Current total P concentration in cropland soils of the Seine basin, according to Delmas et al. [43]. (**d**) Inherited fraction of total P in cropland soils

reduced (Fig. 2b), with P balance becoming even negative in recent periods (Fig. 9a), but the legacy of accumulated P is large enough to keep sustaining high crop productivity for one decade or more [44].

Comparing the regional estimates of cumulated P storage with the data reported by Delmas et al. [43], providing the distribution of measured total P concentration in agricultural soil at the scale of France (Fig. 9c), reveals that the inherited amount of P in cropland accounts for 7–80% of the total stock, with an average value of 23% over the Seine basin (Fig. 9d).

5 Hydrosystem Response to Agricultural Trajectories

Groundwater quality closely reflects the trends of agriculture changes, particularly regarding nitrate concentration, but also pesticide contamination which is dealt with in detail in chapter "How Should Agricultural Practices Be Integrated to Understand and Simulate Long-Term Pesticide Contamination in the Seine River Basin?" As far as surface water quality is concerned, both diffuse sources from agriculture and point sources from urban wastewater together determine their level of contamination. All along the continuum from land to river and to sea, a cascade of transfer, retention and elimination processes affects the budget of nutrients and their ultimate delivery at the outlet of the watershed.

5.1 *Aquifer Storage of Nitrogen*

The central area of the Seine basin is characterised by the presence of large aquifers within sedimentary rock formations (Fig. 1), with decadal groundwater residence time. Nitrate concentrations of these aquifers monitored since the beginning of the twentieth century in several locations (Fig. 11a) show a significant increase from the beginning of the 1960s. The MODCOU model coupled with STICS [20, 21] simulates this evolution in the main aquifer formations (Fig. 10b) and provides a picture of the current level of N contamination in several aquifers at a rather fine resolution (Fig. 10c). The drinking water standard of 11 mgN/l is exceeded in many places.

The model also calculates the recharge of the aquifer formations (infiltration from agricultural, forested and urbanised soils of the basin) and its N concentration and the exfiltration from the aquifer to the river network for the period from 1970 to 2015. As a long-term average, about 56% of the total water runoff of the Seine watershed flows through aquifers, forming the base flow of the river network (with water ages about 10 years), while the rest forms the surface or sub-surface flow rapidly (weeks) reaching rivers. Although no denitrification process is taken into account within the aquifers, the model calculations show that the N flux associated with the base flow is 55% lower than the N flux contributing to the recharge of aquifers. This large budget default can be explained by two processes: (1) water extraction both for irrigation and drinking water provision, currently accounting for about 1.2 Gm^3/year, i.e. 13% of aquifer recharge, and (2) long-term storage of nitrate in the groundwater and the non-saturated zone. Both processes together reduce by more than half the amount of N transferred from watershed soils to the hydrosystem.

5.2 *Riparian Processes*

Before they reach the river bed, flows of superficial and phreatic water coming from the watershed, with their nutrient concentration determined by land use and agricultural practices as discussed above, have to cross a more or less extended riparian area where biogeochemically active superficial soils, often rich in organic matter, are in contact with the river water table. These soils have a significant denitrification capacity, as well as a propensity to reduce iron oxides, thus possibly releasing adsorbed phosphates. Unless the watershed area is equipped with tile drains, by-passing the riparian zone (as is the case in some areas), the flow of nitrate effectively reaching the river is therefore reduced by the denitrification capacity of the riparian wetland. Billen et al. [7] estimated the extent of riparian denitrification in the Seine watershed at 150 $\mathrm{kgN/km}^2$/year. A more recent study, based on the coupling of Riverstrahler with STICS-MODCOU, yields a significantly higher figure of 270 $\mathrm{kgN/km}^2$/year, i.e. 18% of the flux of nitrate coming from base and sub-surface runoff. As expected, this riparian retention mostly occurs in large

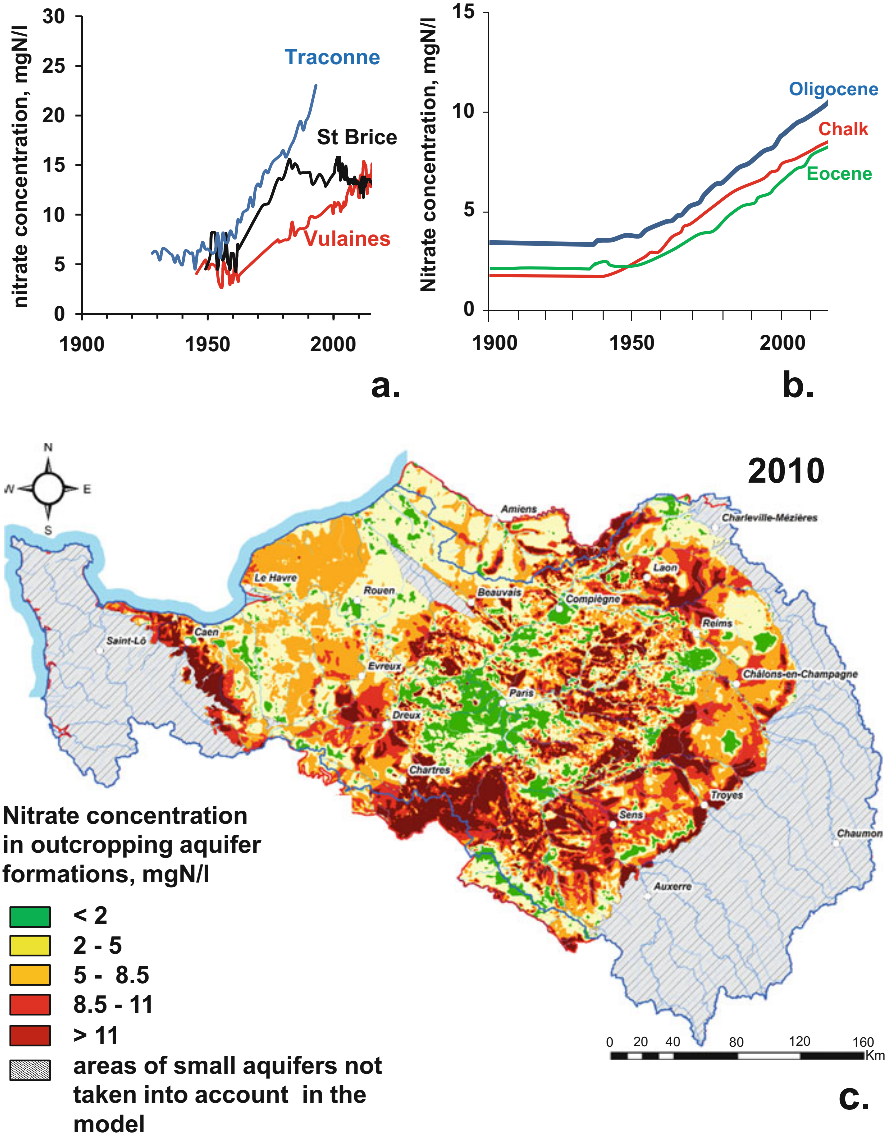

Fig. 10 (**a**) Long-term record of nitrate contamination in some springs in the Seine basin (springs of the Petite Traconne, Saint Brice and Vulaines, Brie limestone formation). (**b**) Long-term simulation of mean nitrate contamination in the major aquifer units of the Seine basin. (**c**) Map of 2010 level of nitrate contamination of sub-surface aquifer systems around the Seine watershed as calculated by the STICS-MODCOU modelling chain [13]

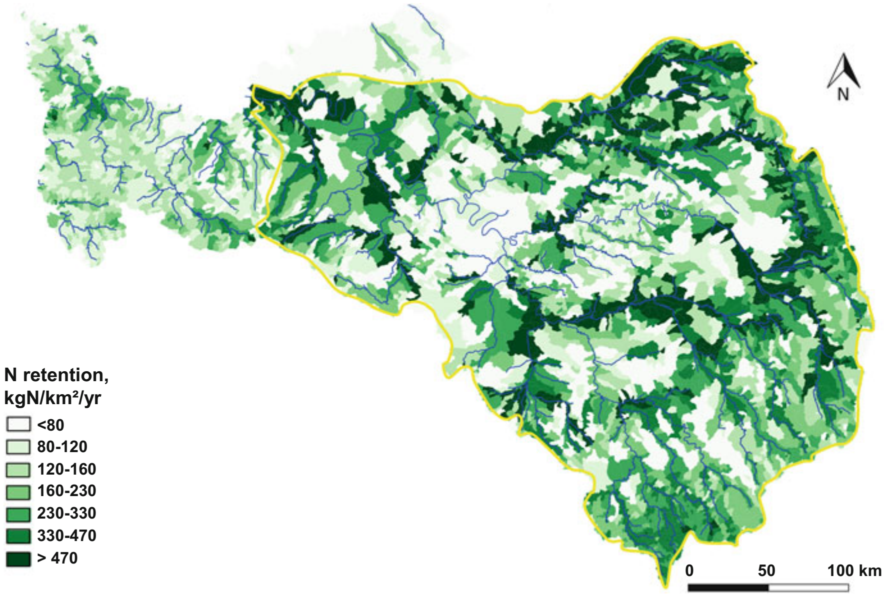

Fig. 11 Distribution of the mean annual flux of riparian denitrification among elementary watersheds of the Seine river system (calculation by the Riverstrahler model coupled with STICS-MODCOU for the 2010–2016 period)

alluvial valleys (Fig. 11), which both have largely developed riparian wetlands and receive substantial nitrate fluxes from the watershed.

Contrary to nitrate, particulate P accumulating downslope in riparian wetlands is prone to being remobilised as dissolved phosphate when anoxic conditions occur, as shown by Gu et al. [45] for the case of Brittany. This process has not been considered in the Seine and could cause higher diffuse P transfer from the watershed to the river system than our estimation based on net erosion fluxes.

5.3 *Point and Diffuse Sources of Nutrients to the River System*

Because of their different response to discharge variations and the different strategy to be implemented for their mitigation, diffuse and point sources of nutrients to the river network have to be distinguished. As far as N is concerned, diffuse sources are dominated by nitrate fluxes from groundwater and surface runoff, after transit through the riparian filter. For P, the diffuse sources are mostly made of the net erosion flux of cropland soils. Point sources are caused by the release of urban and industrial wastewater, eventually after treatment in wastewater purification plants. Their long-term evolution thus results from the combined effects of an increasing

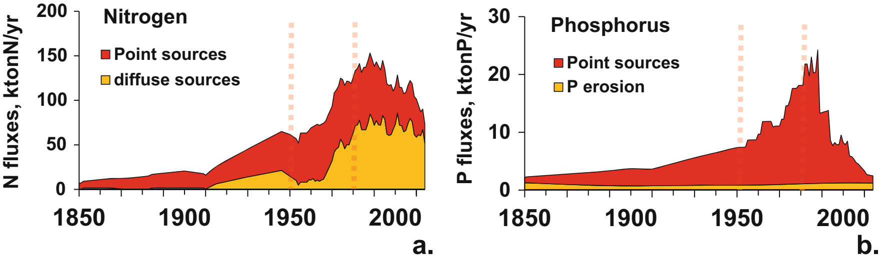

Fig. 12 Long-term variations of point and diffuse sources of N (**a**) and P (**b**) to the river network of the Seine watershed

population in the watershed, the progress of wastewater collection and treatment and the decline of industrial activity. In the case of P, the substitution period of soap with polyphosphate-containing synthetic detergents in the 1970s and 1980s increased domestic P loading by a factor of 3, before P was banned from washing powders in the early 2000s [46]. Figure 12 compares the long-term variations of point and diffuse sources of N and P to the river network of the Seine basin. During the last five decades, diffuse sources of N dominated river loading, and this trend is reinforced in the current period due to the progress in wastewater N treatment [47]. In contrast, for P point sources have always been the dominant source of surface water contamination. However, the spectacular reduction of point sources during the last two decades makes diffuse sources relatively more significant; in the current situation, diffuse and point sources have a nearly equal share in the total P loading of the river system.

5.4 N and P Budget of the Water-Agro-Food System

The concept of the water-agro-food system integrates water quality and agricultural issues, food and feed trade and human diet within a single perspective [46]. The system considered consists of the soils of the watershed, receiving rain and agricultural inputs, the underlying vadose zone and aquifers, the riparian wetlands, the discharging sewers collecting urban wastewater and the river network. Nutrient inputs to this system are the inputs to agricultural soils in excess over export by harvest, as well as point sources from urban wastewater. Only a limited part of these inputs are ultimately delivered by the river flow at the outlet of the basin; a large proportion is transiently retained (for P) or permanently eliminated (for N) along the entire soil-water continuum. Figure 13 gathers the available estimates of the relative value of these different storage or elimination processes and their long-term variations. The soil storage is particularly significant in the case of P, given that it accumulates most of the P brought to agricultural soil in excess of harvest export. Only soil erosion, a process of rather low intensity in the Seine watershed, responds to the increase of soil P by increasing inputs to the hydrosystem.

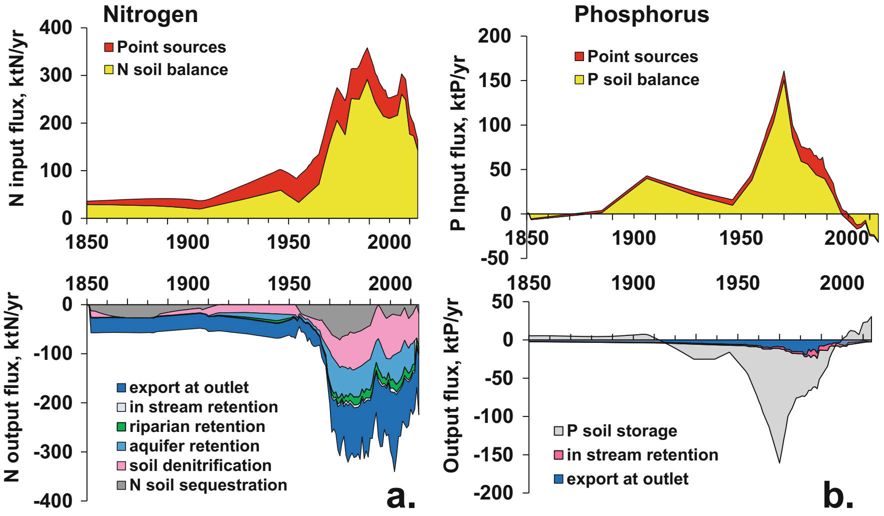

Fig. 13 Inputs and outputs of N (**a**) and P (**b**) fluxes from agricultural soils to the river network over the 1850–2015 period. The upper panels distinguish point sources and soil balance (excess inputs to harvest export); the lower panels show the fate of these inputs as export to the outlet of the watershed or retention/elimination processes in the soils, aquifers, riparian zones and streams

By comparison, N storage in soils is of lower significance and under the control of the soil C cycle. Although periods of increasing agricultural productivity, such as 1955–1980, were characterised by considerable C and organic N storage in cropland soil, most of the N brought to soils in surplus of harvest export is denitrified (in cropland soil itself, in riparian wetlands and to a much lesser extent in the river bed), is stored in the vadose zone and aquifer (the concentration of which takes decades to reach equilibrium) or is exported by the river flow to the outlet of the watershed. These differences in behaviour between N and P in the water-agro system explains the unbalanced nutrient loading delivered by the Seine River to the marine coastal waters of the Seine Bight, which is the source of severe eutrophication problems [9].

6 Conclusion and Scenarios for the Future

6.1 The Importance of Long-Term Storage Processes

Previous attempts at reconstructing the past chemical state of the Seine River [9, 48] were based on the implicit hypothesis of a direct and short-term relationship between land use (and agricultural practices) and diffuse sources of nutrients to the river network. This approach, however, did not account for delays linked to the storage of nutrients in the soil, the vadose zone and the aquifer compartment of the watershed,

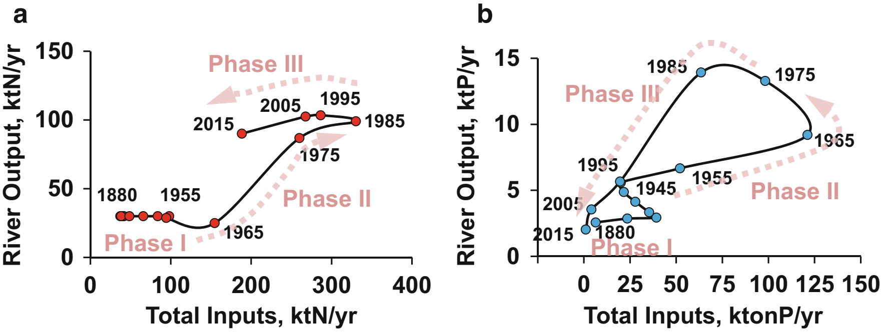

Fig. 14 Trajectory of the Seine River N (**a**) and P (**b**) delivery in response to total inputs to the water-agro-food system from 1850 to 2015 (the data shown represent an average over a 10-year period)

as already discussed by Thieu et al. [49]. In view of the length of these delays, considering long-term historical variations of agriculture is required for correctly understanding soil and water quality: many characteristics of these systems are inherited from past trajectories of agricultural systems. This is particularly true for pools of C and nutrients accumulated in the soil, as well as for nitrate (and pesticides) contaminating groundwater. The role of storage and elimination mechanisms of nutrients along the entire soil-river continuum also explains the non-linear response of the flows of nutrients delivered at the outlet with respect to the long-term changes in nutrient inputs to the water-agrosystem, with distinct hysteresis (Fig. 14). Three phases can be considered in the long-term trajectory of the Seine river system: during phase I, from the mid-nineteenth to the mid-twentieth century moderate increase of inputs are absorbed by retention processes; the short phase II from 1950 to 1975 is a time of rapid increase of nutrient inputs, with a visible response in terms of outputs at the outlet of the river; and phase III is the period of reduction of the inputs, with virtually no response of the outputs in the case of nitrogen, because of the dominance of diffuse sources buffered by aquifers, and a delayed response in the case of phosphorus in so far as point sources are reduced as well as fertilisers inputs. From a management point of view, these mechanisms prevent a rapid improvement of eutrophication conditions, particularly regarding measures taken to reduce diffuse sources of nutrient contamination, as their response to changes in agricultural practices and other environmental management measures may be delayed by several decades.

6.2 The Importance of the Structural Pattern of Agro-Food Systems on the Environmental Imprint

Another important conclusion from the studies summarised in this chapter is the link between the structure of the agro-food system flux pattern and the nutrient environmental losses or accumulation. Indeed, the major trends observed of a gradual intensification and specialisation of agricultural systems are associated with increased opening of the nutrient cycles and growing environmental losses, even though a significant reduction in fertiliser over-use has been observed since the 1980s as a result of agro-environmental regulations (Figs. 1, 8 and 9).

This link is suitably illustrated by two contrasted scenarios for the French agriculture at the horizon 2040, established by Billen et al. [50]. One of these scenarios assumes the pursuit of the trends towards opening to the global market and specialisation of territorial agricultural systems observed over the last 50 years, with, however, compliance to current agro-environmental regulations. The second scenario depicts an alternative option where generalisation of agroecological practices, reconnection of crop and livestock farming and of local food production and consumption, and a change in the human diet towards a Mediterranean diet with a much lower contribution of meat and milk allow a high level of autonomy of the agro-food system of the Seine watershed with respect to industrial and long-distance trade inputs. It was shown that both scenarios can feed the French population at the 2040 horizon and still export a significant amount of cereals, with, however, quite different environmental impacts. Only the latter scenario is able to halve GHG emissions [35] and to improve nitrate (and pesticide) contamination of groundwater and surface water [50]. It has also been shown that solving problems caused by noxious algal blooms in coastal marine waters at the outlet of large, human-impacted river systems would require this type of paradigmatic change in the structure of the agro-food systems [10, 51].

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