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**The water-agro-food system: upscaling from the Seine river basin to the global scale**

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Research article

Geo-hydrological Data & Models

# The water-agro-food system: upscaling from the Seine river basin to the global scale

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**Abstract.** Starting from the study of the major impacts of human activity in the Seine river basin on ground- and surface water quality, due to domestic and industrial wastewater and to intensive agricultural practices, a research framework was developed, combining the analysis of the agricultural systems, their connection to food requirement by local population and trade exchanges with other regions or countries, as well as the losses to the hydrosphere and atmosphere in terms of nitrogen, phosphorus, silica and carbon, and their associated environmental problems. From the Seine basin regional scale, the concept of water agro-food system was enlarged to the national, European and global scales. Coupling the GRAFS approach (Generalized Representation of Agro-Food Systems) to the Riverstrahler model (a biogeochemical drainage network model), allowed to make the link between the different issues of food production, river water quality and nutrient delivery to the coastal zone, as well as to develop an indicator of the risk for coastal water eutrophication (ICEP) now being included as an indicator for the United Nation Sustainable Development Goal (SDG) 14.

**Keywords.** River basin, Water quality, Agro-food system, Modelling, Nutrients, ICEP indicator.

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## 1. Introduction

The PIREN-Seine program (https://www.piren-seine.fr), originating in 1989 as an applied interdisciplinary program devoted to the Seine river system and co-constructed with regional water managers [Billen, 2001], turned out to be a very fruitful source of inspiration for many research studies going well beyond the regional framework. The initial wide and long-term vision and the extreme open-mindedness of its founder, Professor Ghislain de Marsily, are certainly not unrelated to the unprecedented longevity of this still ongoing program.

The local stakes of river management, which were at the origin of the creation of the PIREN-Seine program were mainly related to water quality, endangered by pollution through untreated urban wastewater point release, particularly those of the huge Paris agglomeration (12 million inhabitants), as well as by diffuse sources of agricultural nutrients, pesticides and other toxic compounds [Meybeck et al., 1998, Garnier et al., 2022a]. Large sectors of the Seine River at that time were still oxygen deficient in summer, algal blooms were observed in the main tributaries, groundwater resources were threatened by nitrate and pesticides originating from one of the most intensive agricultural region of Europe, development of toxic algal species occurred in the Seine river plume in the English Channel [Cugier et al., 2005, Garnier et al., 2019b]. The PIREN Seine program, in close

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connection with the Seine Water Agency and other stakeholders involved in the application of National and European directives, contributed to bring about efficient responses to several of these problems, although those linked to agriculture are still far from being solved.

At the same time, the awareness of global environmental issues has grown up. The concept of planetary boundaries [Rockström et al., 2009] defining the safe operating space for humanity with respect to the global Earth System, lead to identify the three major issues at stakes globally: increased greenhouse gas emission leading to climate change, loss of biodiversity and perturbation of the nitrogen cycle. Looking closely, the local stakes of river water management and the major planetary challenges appears as two sides of a same coin.

Here we aim to illustrate the development of the concept of water-agro-food system that gradually emerged from the diverse researches in the PIREN-Seine program. This concept offers a general framework for understanding the major challenges of environmental transition in an integrated view [Garnier et al., 2015, Billen and Garnier, 2021]. The essence of this approach is that of territorial biogeochemistry, derived from the territorial ecology concept [Buclet, 2015, Barles et al., 2011]. It is based on the conviction that most traits of the function of a territory (a geographical space appropriated by a society) are revealed by the analysis of the matter fluxes that cross it and ensure its operation [Billen et al., 2007]. Understanding and modeling these flows requires identifying their main control mechanisms and formalizing them. This can only be done based on a continuous confrontation of the calculated results with the observed field reality, which in turn allows increasing the predictive capacity of the model and its generalization to other situations and its applicability on larger scales. The Seine River system and its watershed have often served as the "demo-case" for conceiving original concepts and methods and to confront them to field reality, before being further applied to other systems and possibly enlarged in scope.

We report the gradual extension of our approach, starting from a renewed vision of river pollution issues established for understanding nutrient flows through the continuum of ecosystems from soil and agricultural systems (including human food requirement and wastes) to river systems and the coastal seas (Land-to-Sea continuums). This approach, although developed on the basis of confrontation with concrete observations at the local or watershed scale, could also be extended to regional and global scales. Further, we will illustrate how such an approach is of considerable help to conceive and explore future visions for the agro-food systems of France, Europe and the World, and specifically one scenario combining changes towards more healthy human diet and a sustainable agro-ecological agriculture, allowing to preserve the quality of water resources and halving greenhouse gas emissions.

## 2. Understanding river water quality

A river can be viewed from different perspectives, among which are (i) a receptacle and an easy way of disposal of wastewater; (ii) an aquatic ecosystem and habitat for fish; (iii) an active conveyor of water and nutrients originating from the watershed to the sea. The challenge of the early PIREN-Seine program was to consider these three perspectives together in a same modelling approach. The water quality models of the 1980's were dominated by the issue of oxygen deficits, a long lasting problem resulting from point wastewater release from Paris city [Gérardin, 1875, Streeter and Phelps, 1925, Lesouëf and André, 1982]. Taking into account the kinetics of microorganisms in the representation of the self-purification processes marked a great progress in the capacity to explain and predict oxygen deficits in the Seine river, not only immediately downstream from the large wastewater discharge from Paris agglomeration, but also 150–200 km downstream, in the Rouen estuarine sector, where ammonia was nitrified after a considerable lag required for the development of a large enough population of nitrifying bacteria [Chestérikoff et al., 1992, Brion et al., 2000, Brion and Billen, 2000, Garnier et al., 2007]. Also, in the 1990's algal development in large rivers became an issue for drinking water production [Garnier et al., 1995, 2005]. Taking into account phytoplankton and bacterial metabolisms in river water quality models opened the way to their transformation into complete aquatic ecosystem models, considering the dynamics of autotrophic and heterotrophic microorganisms, and the related major forms of carbon and nutrients. The RIVE module of the microbiological processes involved in the ecological functioning of aquatic systems since then has grown considerably. It consists now of a generic representation of biogeochemical aquatic processes (Figure 1a). It has recently been fully coded in Python and published under GNU general public license (https://gitlab.in2p3.fr/rive/pyrive). RIVE is shared by a large number of modeling tools such as Riverstrahler [Billen et al., 1994, Garnier et al., 2002], Prose [Even et al., 1998], QualNET [Minaudo et al., 2018], and Barman [Garnier et al., 2000]. With a limited number of kinetic parameters, all of which have been experimentally determined in a variety of aquatic environments, subject to various hydrological and climatic constraints as well as to material inputs from the terrestrial systems, the biogeochemical functioning of these aquatic systems could be satisfactorily modelled.

A river system cannot be considered independently of its relationships with the terrestrial watershed, which controls not only the water flows into the tributaries, but also the quality of its surface water, defining the diffuse sources to the river system. The Riverstrahler model was developed within the PIREN-Seine program as a framework to formalize the relationships between an entire drainage network and the hydrological properties and land use of its watershed [Billen et al., 1994, Garnier et al., 2002] (Figure 1b). The same framework was still adopted in a Python version of the model, called PyNuts-Riverstrahler [Raimonet et al., 2018, Marescaux et al., 2020].

This Riverstrahler model is useful to describe quantitatively how nutrients brought from the watershed either as point or diffuse sources, are transferred, transformed, retained or eliminated during their travel through the drainage network down to the river outlet. Before reaching surface water however, flows of dissolved substances from the surface, sub-surface or groundwater runoff have to cross the riparian system, an often biogeochemically very active zone at the interface between land and river. The processes occurring in this riparian zone, including denitrification and $N_2O$ emissions have been explicitly taken into account in a recent version of the Riverstrahler model [Billen et al., 2018b, 2020a].

While most developments of the Riverstrahler model have been achieved and validated based on observations on the Seine River system, and often motivated by water management concerns in the Seine Basin, the modelling approach was applied to a large number of river systems in France [Garnier et al., 2018b,a, 2019b], Europe [Garnier et al., 2002, Billen et al., 2005, Thieu et al., 2009, Desmit et al., 2018] and other rivers in the world with differing climate and land cover [Nordic rivers, Sferratore et al., 2008; the subtropical Red River, Le et al., 2015].

## 3. Modelling agro-food systems at territorial scale

Understanding the diffuse losses of nutrients to ground- and surface water requires description of how biological material is transformed within the mosaic of terrestrial systems that make up the watershed. Agriculture from that respect plays a major role. Very detailed agronomical models, such as the STICS or EPIC models, are able to calculate the growth of major crops of conventional systems and the associated flows of water and nutrients, including nitrogen leaching, at the plot scale [Williams et al., 1989, Brisson et al., 2003]. Application of such models at larger regional scale has been achieved, and coupled with hydrological models to predict the level of groundwater contamination from a detailed description of farming practices [Ledoux et al., 2007, Beaudoin et al., 2021]. Such a modelling approach, involving the coupling of the EPIC model to a river system model, is also at the core of the SWAT model of water quality in regional watersheds [Neitsch et al., 2001].

There is a need to understand the flows of nutrients involved in agriculture at territorial scale, in relation with structural features of the agro-food system, such as crop- and livestock farming orientations, human diet and trade exchanges of food and feed across the territory. For this purpose, the GRAFS approach (Generalized Representation of agro-food systems) was designed [Billen et al., 2013, 2021, Le Noë et al., 2017, 2018]. GRAFS considers cropland, permanent grassland, livestock and human as the four main compartments where fluxes of nitrogen, carbon and phosphorus are transformed and channelized through the system (Figure 1c). With regards to nitrogen, cropland receives inputs as synthetic fertilizers, manure, atmospheric deposition and symbiotic fixation and transforms them into harvested crops with a surplus at the origin of environmental losses. Livestock is fed partly from harvested crops, from grassland and/or from imported feed.

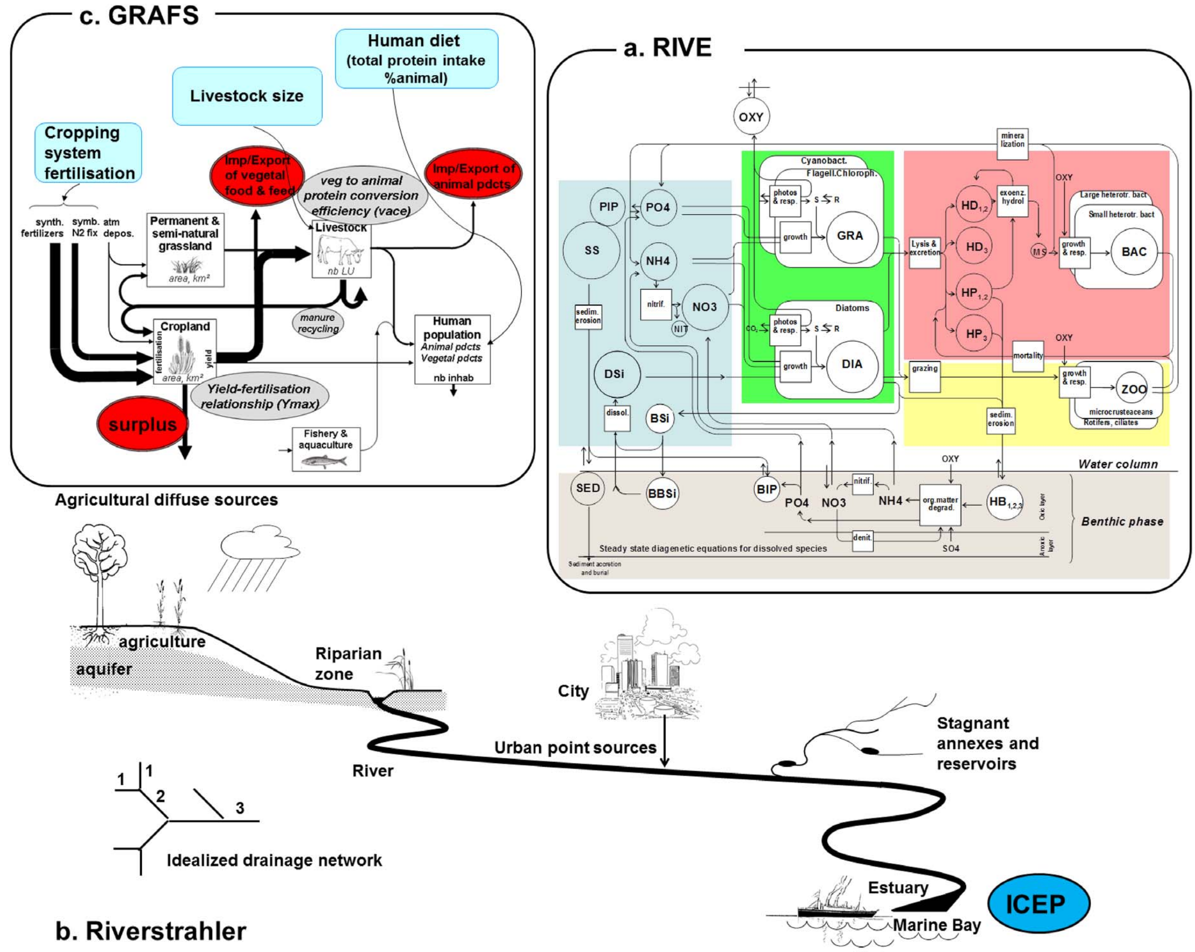


**Figure 1.** Schematic representation the different modelling approaches concurring to the model of the water-agro-food system of a watershed. (a) RIVE module of microbiological processes operating in aquatic ecosystems. (b) The Riverstrahler description of the interactions between the watershed and the river network. (c) The GRAFS model of the agro-food system. Direct connections can be established between the 3 components, leading to a full modelling of nutrient flows through the water-agro-food system.

Human diet, and its share of animal and vegetable food products defines the fate of crop and livestock production, as well as the amount of human excretion. GRAFS can be used as a simple framework for establishing a comprehensive budget of these material flows (N, P, C) within the agro-food system in a given territory based on available agricultural statistics such as fertilizer application, crop areas and production, livestock numbers and production, etc. Alternatively, once such a full budget of material flows has been established, a set of functional relationships linking those fluxes can be calibrated, which then allows GRAFS to be used as a predictive model for the construction of scenarios based on some hypotheses regarding possible changes in the agro-food system.

The most important of these relationships is the one linking harvested yield of the cropping system ($Y$, expressed in nitrogen, kgN/ha/yr) to the total N soil input ($F$, kgN/ha/yr) whatever its form (synthetic fertilizers, manure, atmospheric deposition or symbiotic fixation by legume crops). It has been shown that a robust relationship exists between $Y$ and $F$, integrated over the full crop rotation cycle under given pedo-climatic conditions, whatever the cropping system, either organic or conventional [Lassaletta et al., 2014, Anglade et al., 2015, Le Noë et al., 2017, Billen et al., 2018a]. This yield-fertilization relationship follows a hyperbolic function with a single parameter ($Y_{max}$, in kgN/ha/yr):

$$Y = Y_{max} \cdot F/(F + Y_{max}) \quad (1)$$

$Y_{max}$ thus characterizes the general fertility of the territory. The level of fertilization, with respect to $Y_{max}$, determines the intensity of fertilization (IF, dimensionless):

$$\mathrm{IF} = F/Y_{max}. \quad (2)$$

Related to the shape of the $Y$ versus $F$ relationship, all fertilizing inputs to the soil are not retrieved in the harvested yield. The difference defines the surplus ($S$), or N soil balance. The value of the surplus, which is quadratically related to fertilizing intensity, is a good indicator of total N environmental losses.

$$S = F - Y = Y_{max} \cdot \mathrm{IF}^2/(\mathrm{IF} + 1). \quad (3)$$

The fate of the surplus includes denitrification, sequestration in the soil organic matter pool (when it is aggrading) and leaching. In the case of cropland, the latter is most often the larger share, except in situations where, owing e.g., to water logging, soil denitrification is particularly high, or, due to increased inputs of high C/N residues to the soil, significant sequestration of nitrogen occurs in the soil organic matter.

The second important set of relationships in the GRAFS model link the flow of material through livestock, relating edible production (edProd, in ktN/yr), excretion (Excr, in ktN/yr) and ingestion (Ingest, in ktN/yr), with only two dimensionless parameters, calibrated from observed data in real livestock system, the conversion efficiency of vegetal feed into edible animal products (*cveff*) and the non-edible to edible production ratio (*ned:ed*):

$$\mathrm{eProd} = \mathit{cveff} \cdot \mathrm{Ingest}$$
$$\mathrm{Ingest} = \mathrm{edProd} + \mathrm{Excr} + \mathrm{nedProd}$$
$$\mathit{ned{:}edr} = \mathrm{nedProd}/\mathrm{edProd}.$$

The GRAFS model has been widely used to describe the current agro-food system at different scales, such as the small catchment scale [Garnier et al., 2016], the Seine basin [Billen et al., 2020b], the French agricultural regions [Le Noë et al., 2017, 2018], Europe [Billen et al., 2021, 2022], or the world [Billen et al., 2013, Lassaletta et al., 2016]. It has also been used to interpret the long term past trajectory of the agro-food system of territories. In the case of the Seine watershed and France, the gradual territorial specialization into either intensive cereal cropping systems without livestock farming or intensive specialized livestock systems importing a large share of the feed had been identified as the cause of the opening of the nutrient cycles and increasing N losses to the environment (Figure 2). Similar conclusions have been drawn for other regions [Goyette et al., 2016] and at the global scale [Lassaletta et al., 2016].

GRAFS also calculates the C flows through the agro-food system, including those associated with the non-harvested aerial or underground residues that are returned to the soil and feed the organic carbon pool of the soil, making it possible to address the issue of long term soil C sequestration by coupling GRAFS with a soil C dynamics model such as the AMG model [Le Noë et al., 2019b,a, Garnier et al., 2022a].

For gaseous N losses, empirical relationships with farming practices and climate variables have been established for calculating $NH_3$ volatilization [Sanz-Cobena et al., 2014] and $N_2O$ emission [Garnier et al., 2019a]. As GRAFS calculates N surplus and leaching in all land use of a territory, it can be coupled with the Riverstrahler model for calculating the water quality resulting from a given operation of the agro-food system, allowing retrospective reconstruction of the past water quality [Billen et al., 2007].

## 4. Predicting the risk of coastal water eutrophication

Coastal phytoplanktonic production is controlled by the interplay of several factors including its morphology and hydrological properties as well as nutrient delivery from land base sources or direct discharge. An unbalanced availability of nutrients with nitrogen and phosphorus in excess over silica can lead to the preferential development of non-siliceous, often harmful, algal species rather than of diatoms which initiate linear trophic chains leading to fish [Billen and Garnier, 2007, Garnier et al., 2010, 2021]. Such *new* production of non-siliceous algae, normally restricted to *regenerated* production, is the common characteristics of coastal eutrophication which can

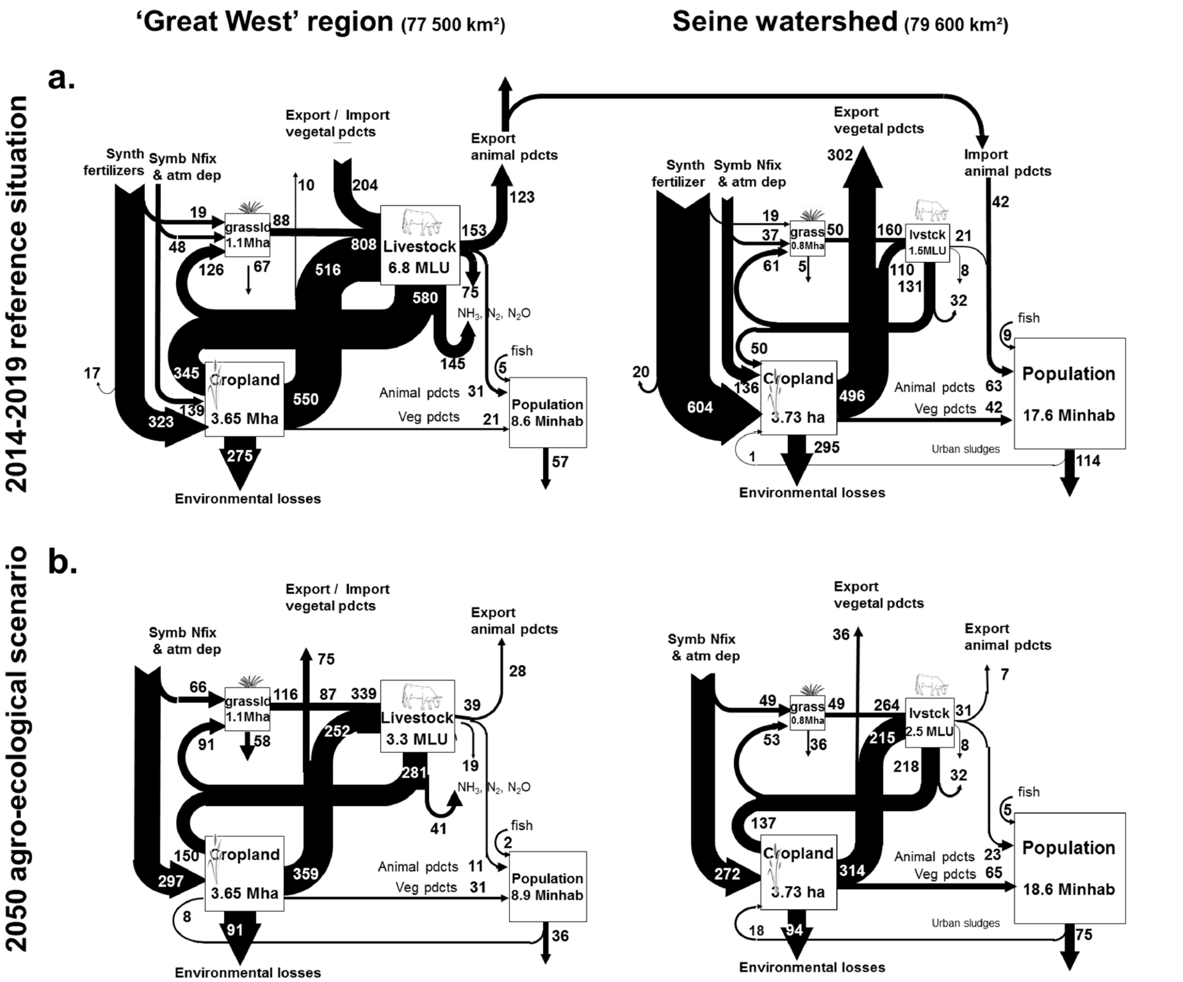


**Figure 2.** N flows (in ktonN/yr) through the current agro-food systems (a) and in a prospective agro-ecological scenario at the 2050 horizon (b) of the Seine watershed and the Great West (Brittany, Basse Normandie, Pays de la Loire) region. Both regions have a very close surface area. The former is characterized by a much higher population and agriculture oriented toward cereal production for export. The latter is more oriented toward intensive livestock farming, with animal products exported to the rest of France. (All flux values are extracted from the study at European scale by Billen et al., 2022.)

results in very diverse manifestations such as the accumulation of mucilaginous material, toxin production, or oxygen deficits caused by degradation of accumulated unpalatable algal biomass.

The ICEP has been proposed by Billen and Garnier [2007] as an indicator of the eutrophication potential of nutrient delivery by river watersheds. It is defined as the excess of N or P over Si with respect to the requirements of balanced diatoms growth (according to Redfield ratios) and is expressed in kgC/day/km$^2$ (i.e. an algal biomass potentially produced per km$^2$ of watershed) for a direct comparison of N-ICEP and P-ICEP among river systems:

$$\text{N-ICEP (kgC/d/km}^2) = [\text{FlxN (ktonN/yr)}/14 * 16 - \text{FlxSi (ktonSi/yr)}/28 * 20] * 106 * 12/365/\text{Wa (km}^2)$$

$$\text{P-ICEP (kgC/d/km}^2) = [\text{FlxP (ktonP/yr)}/31 - \text{FlxSi (ktonSi/yr)}/28 * 20] * 106 * 12/365/\text{Wa (km}^2)$$

where FlxN, FlxP and FlxSi (kton/yr) are the average annual river loads of nitrogen, phosphorus and silica respectively, and Wa ($km^2$) the watershed area.

N- or P-ICEP is preferred according to the most limiting element in the marine environment.

The ICEP permits to assess the potential for non-siliceous algal growth to be sustained by N and P in excess over silica in the nutrient load of a given river and can easily be calculated by the Riverstrahler model, at the outlet of large rivers discharging into coastal seas (Figure 3a).

The ICEP indicator has recently been included as an indicator for marine eutrophication in the UN Sustainable Development Goals (SDG14: https://sdg.iisd.org/news/ioc-unesco-provides-update-on-sdg-14-indicator-development/).

The ICEP indicator does not take into account any characteristics of the receiving coastal zone. Yet, according to their morphological and hydrological peculiarities, the pelagic ecosystem of different bays can react quite differently to a given loading of nutrients. For this reason, a derived indicator, the B_ICEP (for Bay integrated indicator of coastal eutrophication potential) was further developed, combining ICEP with some characteristics of the specific receiving Bay [Garnier et al., 2021]. It is defined as the ratio of the riverine flux of nutrient in excess over silica to the volume of the receiving bay multiplied by its flushing rate.

$$\text{B\_ICEP (mgC/L)} = [\text{ICEP (kgC/d/km}^2) * \text{Wa (km}^2) * 1000] / [\text{Volb (m}^3) \cdot \text{fr (d}^{-1})]$$

where Wa is the watershed area ($km^2$), Volb ($m^3$) is the volume of the receiving bay, and fr the flushing rate of the bay by both marine currents from the surrounding sea water bodies and by the river flow. The flushing rate (fr) of a given bay can be empirically estimated based on its average salinity SalB(‰) compared with that of the surrounding seawater bodies.

So defined, the B-ICEP represents the maximum concentration of non-siliceous algae which can be developed based on excess riverine N and P over Si in a particular marine bay. The pertinence of the B_ICEP approach, i.e., the ability of this indicator to predict the order of magnitude of undesirable algal blooms in particular bays, has been demonstrated by using an idealized model of marine algal development [Garnier et al., 2021].

## 5. Integrated agro-ecological scenarios of future water-agro-food systems

The modelling chain GRAFS—Riverstrahler—B_ICEP has the potential for an integrated assessment of water quality over the whole continuum from headwaters to coastal sea resulting from a given scenario of the agro-food system. Here, as an example of the approach, we will explore some results from an extreme scenario which makes the assumption of a generalization of agro-ecological practices in agriculture. The purpose is to assess the capacity of such a scenario, which would consider organic farming without recourse to synthetic fertilizer, to feed the human population, as well as its effect on water quality and coastal eutrophication, and its ability to reduce greenhouse gas emission.

Three major levers have been combined in conceiving the scenario. The first one concerns human diet. WHO [2019] considers a protein intake of 3.4 kgN-protein per capita per year, as the vital minimum requirement. Values twice as high are observed in western countries, and have been associated to important health problems [Willet et al., 2019]. Importantly, the share of animal-based protein consumption varies between less than 10% in some African countries to as much as 70% in rich western countries in Europe and the USA. The EAT-Lancet Commission recently recommended a Reference Healthy Diet which, compared to the current European diet, implies a strong reduction not only of total protein intake but also of the share of animal products Willet et al. [2019] The assumption of the agro-ecological scenario presented here is very close to the EAT-Lancet one (Table 1).

The second lever of the agro-ecological scenario is the adoption of organic farming practices, strictly banning the use of synthetic inputs (fertilizers and pesticides). There is large diversity of such practices world-wide, often adjusted by the experience of farmers to territorial climatic peculiarities [Altieri, 2002, Altieri and Nicholls, 2017, Compagnone et al., 2018, Garnier et al., 2016, Billen et al., 2021]. All of them use long and diversified crop rotations leaving ample room to grain and forage legumes, the symbiotic $N_2$ fixation of which constitutes the main source of new fertilizing nitrogen input to the whole rotation. An extensive review of organic systems effectively in use in Europe led to a typology of these crop

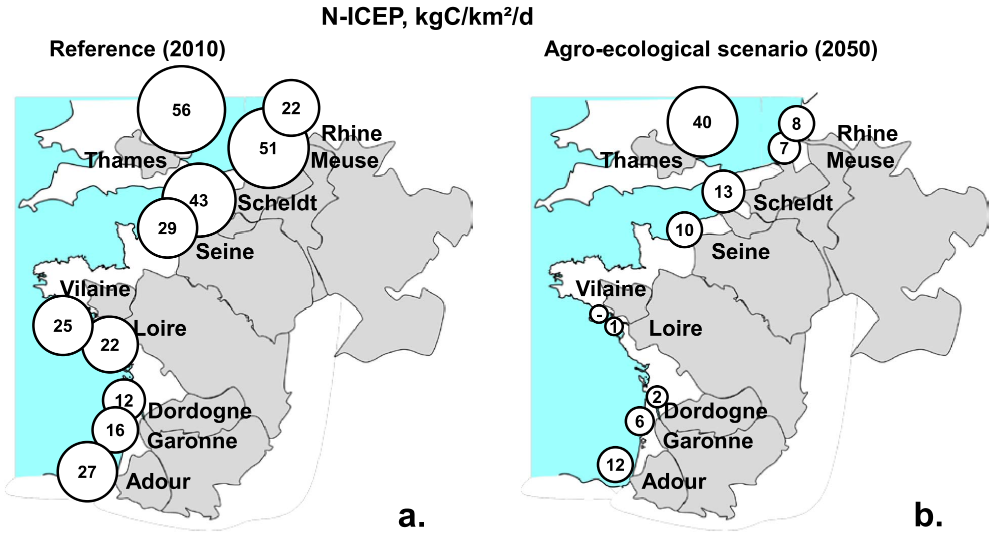


**Figure 3.** Values, linked to different sizes of circles for ICEP (Indicator of Coastal Eutrophication Potential, in kgC/km$^2$/day) at the outlet of the main rivers discharging along the North Atlantic façade. (a) Current situation (2010); (b) in the agro-ecological scenario. (The data are extracted from the Emosem program, Desmit et al., 2018.)

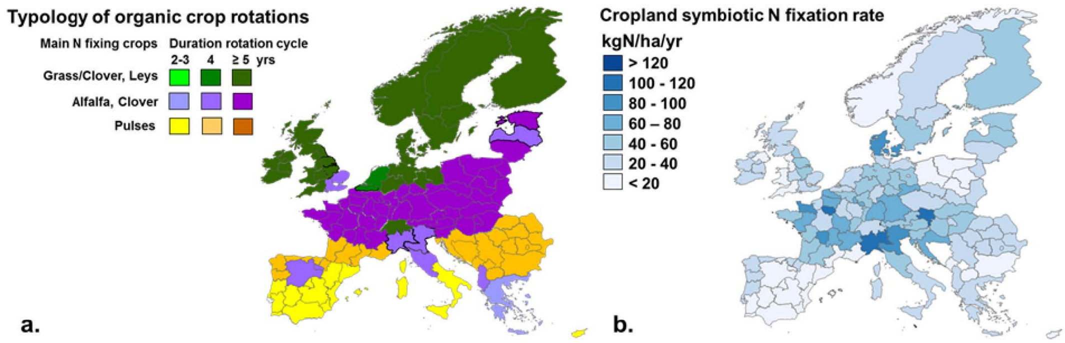


**Figure 4.** (a) Typology of organic crop rotation in Europe [Billen et al., 2021] and (b) associated symbiotic $N_2$ fixation capacity [Billen et al., 2022].

rotations, and to an estimate of their $N_2$ fixation capacity (Figure 4).

The third lever to be operated in such a scenario concerns the reconnection of crop and livestock farming. Animals have not only the function of providing meat and milk to human: they are also the agent able to convey nutrients from legumes to other crops and from grassland to cropland. In our scenario, livestock density in each region is determined by the available resources of grass and forage crop production, with no recourse to feed imports from outside.

The results of the application of this scenario to the two contrasting regions taken as examples above, the Seine basin and the Great West, are illustrated in Figure 3b. The scenario would lead to reintroduction of livestock in the center of the Paris basin, while its density would be strongly reduced in Brittany. In the scenario, both regions would feed their human and livestock populations without import of feed and would still export ample food surpluses. Similarly, at the scale of France, this scenario predicts that

**Table 1.** Current average European diet per day (d) or per year (yr) in terms of apparent consumption [Westhoek et al., 2015] and prospective diet considered in the agro-ecological scenario exposed in this paper at the horizon 2050, close to the EAT-Lancet reference healthy diet

| | | | Average current European diet | | | | Prospective healthy diet 2050 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | kcal/g | %N | g/d | kcal/d | kgN/cap/yr | % | g/d | kcal/d | kgN/cap/yr | % |
| Vegetal products | | | | | 2.35 | 41 | | | 3.5 | 70 |
| Cereals | 3.5 | 2 | 240 | 840 | 1.75 | | 285 | 998 | 2.08 | |
| Grain legumes | 1 | 3.5 | 15 | 15 | 0.19 | | 59 | 59 | 0.75 | |
| Roots and tubers | 0.8 | 0.25 | 100 | 80 | 0.09 | | 80 | 64 | 0.07 | |
| Fresh vegetables | 0.3 | 0.3 | 150 | 45 | 0.16 | | 300 | 90 | 0.33 | |
| Fresh fruits | 0.3 | 0.15 | 140 | 42 | 0.08 | | 200 | 60 | 0.11 | |
| Nuts | 6.5 | 1 | 20 | 130 | 0.07 | | 50 | 325 | 0.18 | |
| Animal products (excluding fish and seafood) | | | | | 3.15 | 54 | | | 1.25 | 25 |
| Milk products | 0.8 | 0.7 | 565 | 452 | 1.44 | | 224 | 179 | 0.57 | |
| Meat | 1.5 | 3.25 | 125 | 188 | 1.48 | | 50 | 74 | 0.59 | |
| Eggs | 1.4 | 2 | 30 | 42 | 0.22 | | 12 | 17 | 0.09 | |
| Fish & seafood | 1 | 2.9 | 27 | 27 | 0.29 | 5 | 23.5 | 24 | 0.25 | 5 |
| Products without N | | | | | [kgNeq/cap/yr]* | | | | [kgNeq/cap/yr]* | |
| Added sugar | 3 | 0 | 50 | 150 | 0.24* | | 20 | 60 | 0.09* | |
| Oil | 7 | 0 | 40 | 280 | 1.10* | | 40 | 280 | 1.10* | |
| Total | | | 1502 | 2291 | 5.78 | 100 | 1343 | 2229 | 5.0 | 100 |

Europe refers here to the EU28 plus UK, non EU ex-Yugoslavian countries, Norway and Switzerland.

*Nequivalent in corresponding harvested product before extraction of oil or sugar (0.075 equN/kg oil and 0.013 kgN/kg sugar).

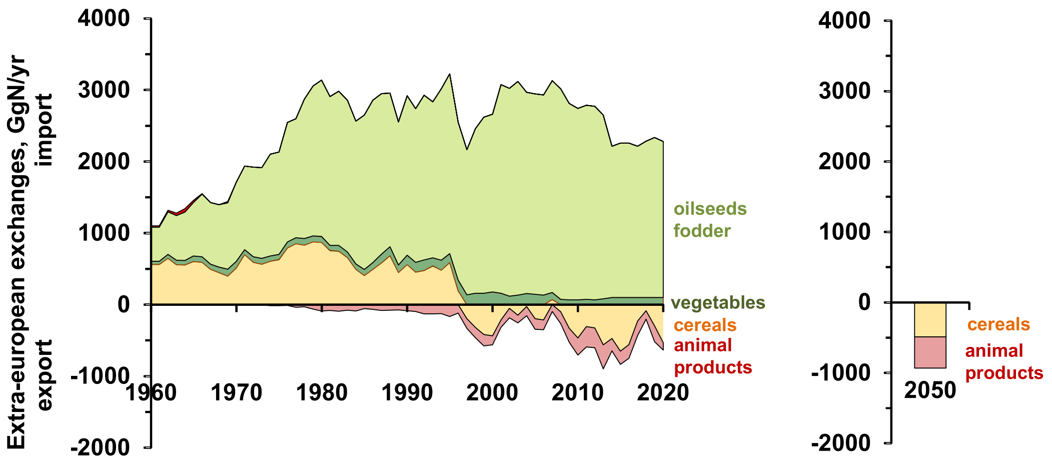


**Figure 5.** Extra-European exchanges of cereals, animal products, oilseed fodder and vegetables from 1961 to 2020 [Billen et al., 2021 and FAOstat data] and in the agro-ecological scenario for 2050 [Billen et al., 2022].

French exportation could still amount 220 ktN/yr as vegetable products (40% of the current value) and 3 ktonN/yr as animal products (10% of current exports), without importing any soybean based feed [Billen et al., 2018a]. For Europe the conclusions are similar: the agro-ecological scenario would be able to feed the population without synthetic N fertilizers while still exporting cereals and animal products at rates similar to current levels to the rest of the world (Figure 5).

At the global scale, the possibility of feeding a population of 10 billion people by agro-ecological agriculture, with no deforestation, and less recourse to international trade (hence more food sovereignty) was demonstrated by several authors [Billen et al., 2015, Lassaletta et al., 2016, Erb et al., 2016], provided that a diet not exceeding 30–40% of animal products in the total protein ingestion is adopted everywhere. This work thus demonstrate that, contrarily to what is sometimes reported [Connor, 2013, 2018, Barbieri et al., 2021], agro-ecological practices can feed the world provided they are combined with dietary changes and structural reorganization of the relationships between crop and livestock farming, allowing to close the nitrogen cycle.

The effect of this scenario on water quality can be assessed by comparing the leaching water nitrate concentration calculated by the GRAFS model between the current and the scenarized situation (Figure 6). Further, coupling GRAFS and Riverstrahler models shows how nitrate concentration would be reduced in the drainage network of the different rivers of the Western Atlantic façade and English Channel [Desmit et al., 2018, Garnier et al., 2019b, 2022b], reducing the risks of coastal eutrophication (Figure 4b).

Greenhouse gas emissions by agriculture are also predicted to be drastically reduced in this agro-ecological scenario, owing to reduced livestock numbers (hence reduction of methane emissions) and suppression of synthetic N fertilizers (hence reduction of $CO_2$ emissions for fertilizer synthesis and $N_2O$ emissions from cropland (Figure 7).

For the Seine Basin, the Great West and France as a whole, the contribution of agriculture to total greenhouse gas emissions in terms of $CO_2$ equivalent is estimated to have reduced by 33%, 74% and 50% respectively [Garnier et al., 2019a, 2022a].

## 6. Conclusions

The water-agro-food continuum concept, gradually developed in the past 30 years, was a guide for dealing with the tremendous complexity of the intertwined challenges of food production, international trade, environmental quality and climate changes. It stresses the central role that agriculture and food supply play in a globalized world. It has helped conceiving a vision of our future where these challenges would be met altogether. These challenges are global in nature as they ultimately concern the whole planet. However, the solutions, just like the research on which they are based, needs to be rooted in territories. The Seine watershed, from that perspective was a very fruitful case study, because it is a paradigmatic example of a territory organized around a huge metropolis of global significance, ans well as a highly specialized agricultural area with extremely intensive farming practices. This is likely to be one of the main reasons for the exceptional longevity and productivity of the PIREN-Seine program.

## Conflicts of interest

Authors have no conflict of interest to declare.

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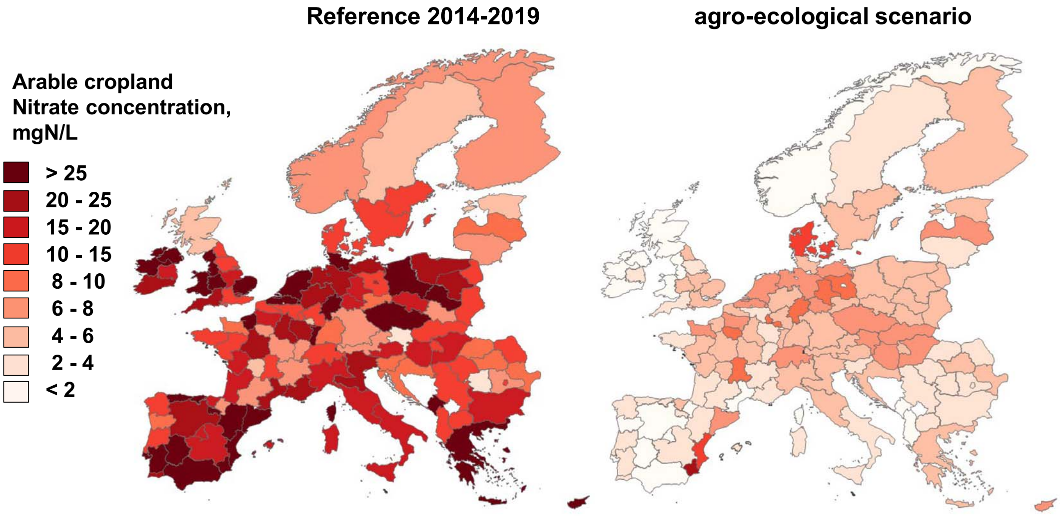


**Figure 6.** Cropland leaching water N concentration (in mgN/l) calculated from N surplus and runoff in the different European regions in 2014–2019 and in the agro-ecological scenario [data from Billen et al., 2022].

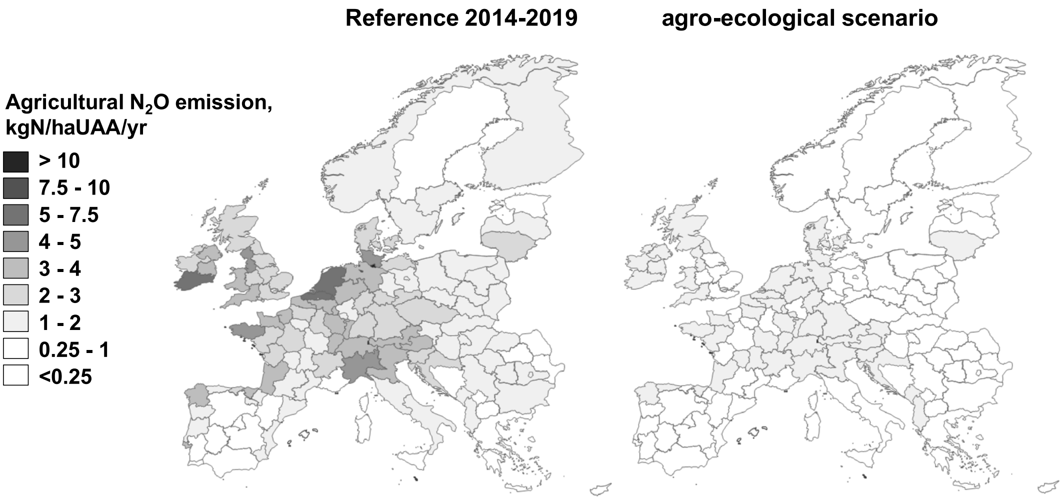


**Figure 7.** Total agricultural $N_2O$ emission in the different European regions in 2014–2019 and in the agro-ecological scenario [data from Billen et al., 2022].

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