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ABSTRACT

Nitrate and pesticide contamination of surface and groundwater has become a major problem in intensive farming regions in Europe, with nitrate concentrations reaching values above the standard defined in 2000 by the European Water Framework Directive. In the Seine basin, a major issue is the closure and abandonment of drinking-water wells, which force water managers and drinking-water producers to explore solutions for water resource protection. Organic farming has appeared as a credible alternative to conventional farming, and this study explores the potential of organic farming to reconcile agricultural production and water quality. On the basis of agricultural statistics, survey questionnaires and experimental data, the nitrogen soil surface balance (N-SSB) has been established at the scale of a small 104-km^2 catchment (The Orgeval sub-basin), representative of the intensive cash crop farming in the Seine basin. The N-surplus for arable land in specialized organic cash crop systems has been found to be half that of current conventional systems (15 kg N ha^{-1} yr^{-1} versus 30 kg N ha^{-1} yr^{-1}, respectively). The N-yield in organic systems is 21% lower than in conventional systems, but total fertilization (mostly symbiotic N fixation) is also 26% lower. Whereas 2–3 years of forage legume (e.g., alfalfa) as a starter crop of the typical 7- to 10-year diversified rotation builds up N soil fertility and helps prevent weeds without pesticides, the existence of an outlet for this fodder production is a limiting factor for the economic sustainability and the environmental benefits of these farming systems. Therefore, we explored the possibility of a reconnection of livestock and crop farming systems in the Orgeval catchment, a traditional dairy farming and Brie cheese production region. We calculated the N-SSB for this type of a reconnected livestock and cropping system and found a value very close to the specialized organic cash crop system with full utilization of fodder production, leading to profitable animal production, essentially as milk in this farm design. This reconnected system is compared with the estimated situation in 1955 before separation of plant and livestock production. Furthermore, the N-SSB values were converted into infiltrating sub-root concentrations and used as a boundary condition to a biogeochemical model. Organic cropping and organic reconnected livestock cropping systems result in a 50% reduction of surface water nitrate concentrations, a surface water quality 20% better than that reconstructed for 1955, with an overall higher protein production.

1. Introduction

Industrial agriculture and the use of nitrogen fertilizers have led to the massive introduction of reactive nitrogen (N) into the biosphere, which subsequently cascades through a number of

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environmental compartments (Galloway et al., 2003; Sutton et al., 2011). Nitrate contamination of water, loss of biodiversity, and atmospheric pollution are among the major threats (Good and Beatty, 2011; Sutton et al., 2011). Whereas phosphorus from domestic wastewater has been considerably decreased in the past 15 years, improving surface water ecosystem quality (Passy et al., 2013; Romero et al., 2013), N leaching, although better controlled owing to good agricultural practices, continues to contaminate ground- and surface water from which drinking water is produced (IFEN, 2004). N fluxes at the coastal zones of intensively cropped watersheds are far in excess in regard to phosphorus and silica, causing coastal eutrophication with subsequent ecological (harmful algal bloom, hypoxia, fish kills, etc.) and economic problems (fishing, tourism, etc.) (Lancelot et al., 2011; Passy et al., 2013; Glibert et al., 2014). N fertilizers also cause N_2O and NOx emissions, greenhouse gases involved in atmospheric warming (Bouwman et al., 2002) as well as NH_3 volatilization, an irritating gas forming fine particles with negative impacts both on human health (Schiffman et al., 2001; Goss et al., 2013) and causing ecosystem damages (e.g., soil acidification when redeposited, Erisman et al., 2008; Sutton et al., 2011).

The increasing introduction of mineral fertilizers after World War II is not the sole change in farming systems. Increasing specialization of agricultural systems at the scale of whole regions and countries has also been observed in the last decades (Naylor et al., 2005; Lassaletta et al., 2014a; Bonaudo et al., 2014; Lemaire et al., 2014; Peyraud et al., 2014; van Grinsven et al., 2015). Loss of biodiversity, both by shortening crop rotations and reducing the heterogeneity of rural habitats, also contributes to making modern agriculture unsustainable (Tomich et al., 2011). To overcome the environmental problems related to industrial and specialized agriculture, a great challenge of this early 21st century is elucidating how future agriculture will be able to enjoy good water quality with a nitrate concentration below the limit for drinking water production and to give rise to a better ecological status of water masses by avoiding coastal eutrophication, while feeding the increasing world population. Alternative farming systems involving greater diversity have often been put forward as a solution (Altieri, 2002; Tilman et al., 2001, 2011; Thieu et al., 2011; Staudacher et al., 2013; Plaza-Bonilla et al., 2015a). In addition, local reconnection between livestock and crop production systems has been suggested as an effective approach closing the N (and phosphorus) biogeochemical cycle that industrial agriculture has widely opened (Naylor et al., 2005; Tomich et al., 2011; Lemaire et al., 2014; Bonaudo et al., 2014; Sasu-Boakye et al., 2014; Nesme et al., 2015).

The center of the Seine basin in the North of France is typically one of these intensive and specialized cropped areas. Increasing N concentrations in ground- and surface waters has been clearly related to the amount of mineral fertilizers massively applied since the 1970s (Billen et al., 2007). Furthermore, the disconnection between crop and livestock has been evidenced (Mignolet et al., 2012). Livestock is today relegated to the periphery of the Seine watershed, which otherwise is mostly devoted to cash crop farming (Mignolet et al., 2007), exporting most production on the international market, whereas animal farming is concentrated in Brittany, with a high dependence on soybean import from South America (Billen et al., 2012). In both areas, high soil N surpluses cause ground- and surface water contamination. The consequences in coastal marine areas of the Seine Bight are recurrent toxic events (Cugier et al., 2005; Romero et al., 2013; Passy et al., 2016), whereas excess algal biomass on the coast of Brittany makes the headlines of the newspapers every summer (Ouest France, 2014, 2015).

To address the question of agriculture and water quality, we have chosen to study a small catchment of the Seine basin, the Orgeval (104 km^2), which is well documented (Garnier et al., 2014) and representative of the present specialized crop intensive agriculture, despite the lack of rapeseed and the occurrence of a few diversification crops such as faba beans and flax. Traditionally, the Orgeval catchment was located in a dairy region called the "Brie laitière," producing Brie cheese. Today, local dairy producers can be counted on the fingers of one hand and Brie cheese is mainly produced with milk imported from other regions.

A major objective of this study was to calculate the N soil surface balance (N-SSB) at the scale of the catchment for past, present, and possibly future agricultural systems. For the past, the statistics in 1955 were chosen corresponding to the time just before the Rome Treatise (1957) when the Common Agricultural Policy was created, although applied from 1962 only.

To reduce N leaching to the aquifers and N contamination of surface waters, we calculated the N-SSB considering the framework of organic farming systems that has been shown to reduce N losses (nitrate leaching and N_2O emission) by about 20–30% (Benoit et al., 2014, 2015a). In this region, organic farming systems are characterized by a complex crop rotation (7–10 years), alternating cereals with 2–3 years of alfalfa and N-fixing grain legumes. Since forage legumes make up a large fraction of total crop production, the economic viability of these systems depends a great deal on the existence of a local outlet for their legume crops. We therefore explored the possibility of an integrated organic farming system reconnecting crop and livestock, in which cattle are fed with forage legume crops and grassland, and local land-based livestock manure is used as fertilizer. For the different farming systems described or simulated, we explored the resulting effects in terms of surface water contamination using a biogeochemical river-system water-quality model.

2. Study site

The Orgeval watershed is a rural small sub-catchment covering 104 km^2, located 70 km east of Paris (France) in the Seine basin (Fig. 1). It is highly homogenous in terms of climate (semi-oceanic), topography (mean altitude, 148 m) and soils (deep loamy soils). Land use is mostly agricultural land (82%), completely tile-drained, dominated by cereal crops with conventional practices, mainly based on mineral N fertilization inputs, presently at a rate of about 150 kgN ha^{-1} yr^{-1}. The Orgeval catchment is characteristic of the center of the Seine basin, in terms of agricultural systems and practices. It has a small population, 4100 inhabitants, i.e., about 40 inhab. km^{-2}.

Based on detailed questionnaires and interviews carried out since the 1990s (Schott et al., 2014), the main crop rotations on arable land have been established. They are dominated by winter wheat (55% of the utilized agricultural land), maize grain (15%), faba bean (13%, replacing pea affected by the *Aphanomyces* fungi since the late 1990s), sugar beet (5%), and flax (5%) (Fig. 2). Rapeseed, known for its negative effect on drainage infrastructures, is unusual in this 90% tile-drained catchment.

Based on the French national agricultural statistics (Agreste, Recensement Agricole, http://www.agreste.agriculture.gouv.fr), we reconstructed the changes in the proportion of arable land and grassland and in livestock composition (Fig. 3). The year 1955 was studied as a reference period before the Common Agricultural Policy which aimed at increasing agricultural productivity in an effort to reach European food self-sufficiency. Data are available at the municipality level for 1955 (18 "communes" in the watershed). For the years 1970, 1979, 1988, 2000, and 2010, data are available at administrative districts level (four "cantons" in the Orgeval catchment) due to statistical confidentiality (while the surface area of the farm increased, their numbers decreased and a few left at the municipality level could be easily identifiable). Grassland, which accounted for about 20% of the

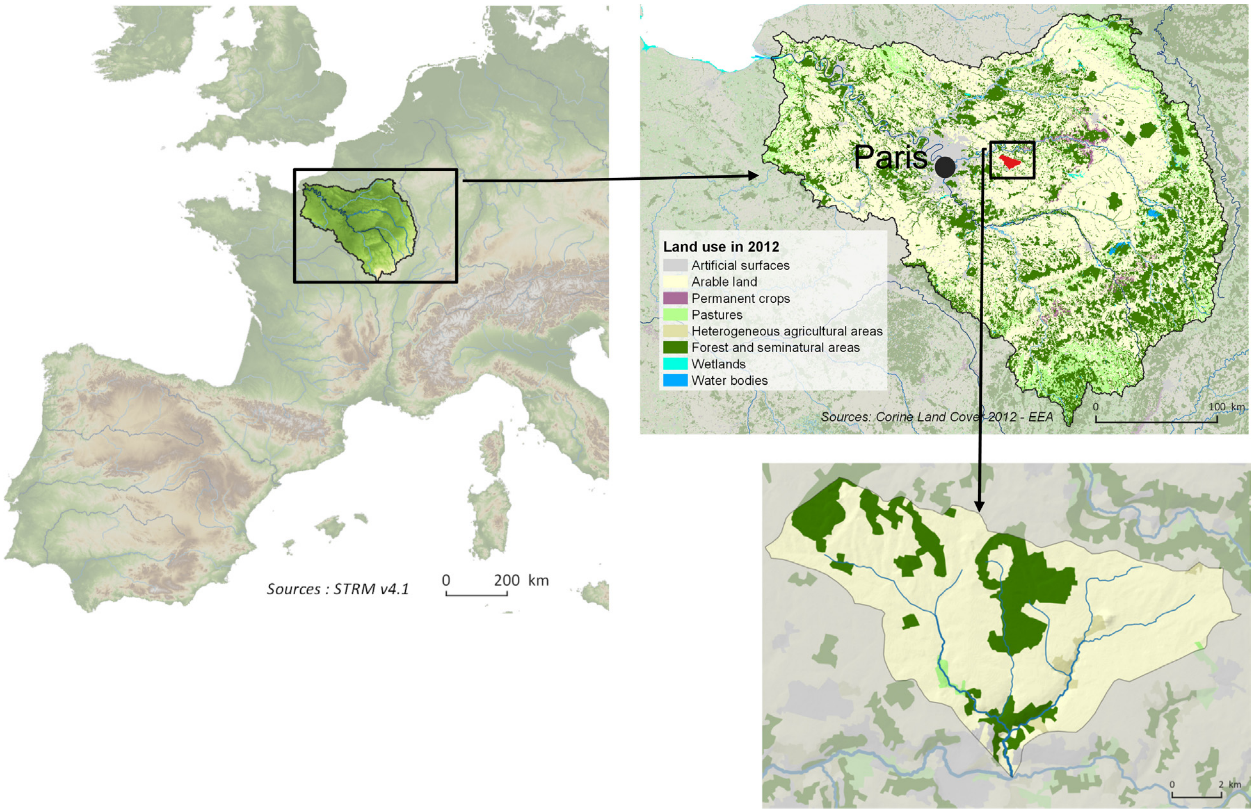

Fig. 1. Situation of the Orgeval catchment in the Seine basin of the north of France. Land use map according to Corine Land Cover 2012.

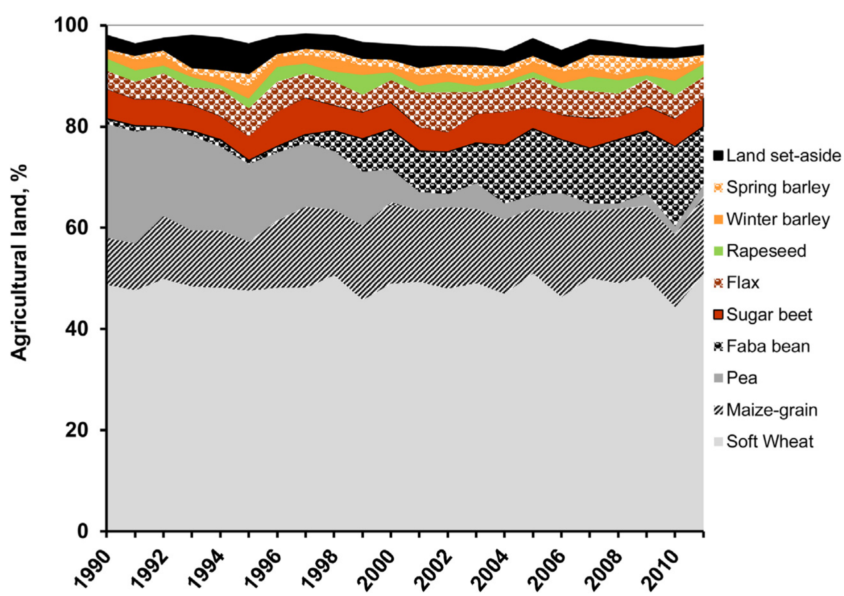

Fig. 2. Changes in the crop rotations in the Orgeval catchment between 1990 and 2011 (source: APOCA database, Nicola et al., 2012, based on farmer questionnaires).

utilized agricultural land until the early 1970s, has decreased to 7% today. Livestock, which reached 0.5 livestock units per hectare in 1955, decreased rapidly to less than 0.2 livestock units per hectare in 1970 and has stabilized at around 0.1 livestock units per hectare over the last 20 years. Because soils where grasslands are located are mostly hydromorphic and hardly cultivable, their rate of decline was lower than the one of the livestock in a trend of agriculture de-intensification. These changes indicate a specialization in cash crop production, possible with tile-drainage of waterlogged soils. Since the end of the 18th century, wetlands have been considered as unhealthy by most hygienists (Derex, 2001). Although this dairy region ("Brie laitière") still produces traditional cheese on a few of the region's farms, most of the production of Brie cheese is made industrially, with milk produced in other French regions, mainly in the Meuse department, north-east France (which is allowed by the AOC – *Appellation d'Origine Contrôlée*- a French certification attributed to typical regional products, e.g. wines, cheeses, etc.).

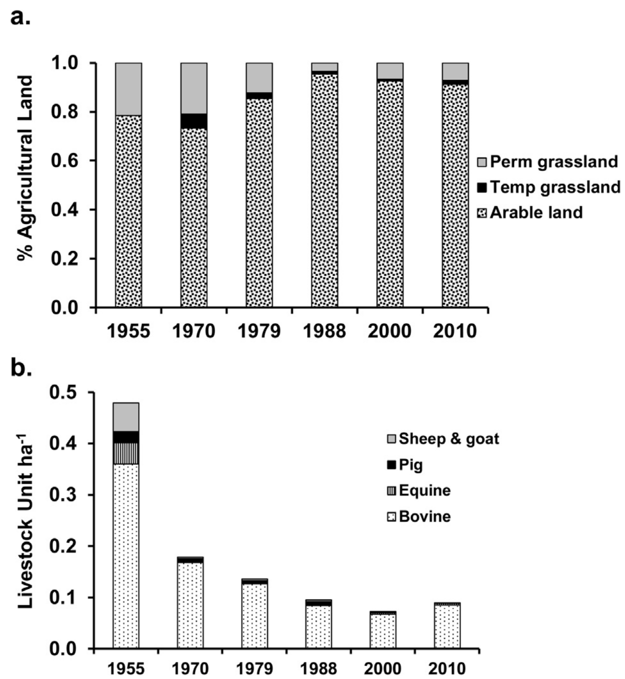

Fig. 3. Changes in (a) the percentages of agricultural land in terms of permanent and temporary grassland, and arable land; (b) livestock unit per hectare for major animals of the livestock (cattle, horses, pigs and sheep and goats) from 1955 (Agricultural Statistics, statistiques agricoles de la France, Ministère de l'Agriculture).

3. Methodology

This study was based on two complementary approaches. On one hand, we characterized agricultural practices and their associated N fluxes and environmental losses by calculating the N soil surface balance for the region's current dominant conventional cropping systems as well as for the typical organic farming systems, although the latter currently account for less than 2% of the utilized agricultural land. Both systems have been documented by literature data and agricultural statistics, our own measurements, as well as detailed questionnaires and interviews of individual farmers (rotations of 44 farms and 19 technical arrangements applied by the farmers), as reported by the data base named Agricultural Practices of the Orgeval Catchment Area (APOCA, Nicola et al., 2012; Schott et al., 2014). On the other hand, the Riverstrahler modeling approach and its GIS interface (Ruelland et al., 2007) was implemented to simulate the impact of agricultural practices and their N losses to the environment on water quality in the river catchment.

3.1. Nitrogen soil surface balance

For all the different land areas studied – whether they are a plot, a farm with its crop rotation, or a territory – the N-SSB (Oenema et al., 2003; Anglade et al., 2015a) takes into account (i) the total N inputs (mineral and/or organic fertilizers, atmospheric deposition, and biological N fixation) and (ii) the total N outputs (harvested crops and grazing). Integrated over a full rotation cycle, the difference between inputs and outputs gives the N surplus, which is a proxy for N losses to the environment, contaminating the hydrosystem via nitrate leaching, or the atmosphere by the N_2O by-products of denitrification, or NH_3 volatilization.

Exogenous inputs and yields are provided by the databases used (statistics and/or questionnaires), while biological nitrogen fixation is estimated from yields, using the relations established by Anglade et al. (2015b) for six legume species commonly grown in the area studied. N inputs from atmospheric dry and wet deposition were obtained at a department level from the EMEP (European Monitoring and Evaluation Program, available at www.emep.int/mscw). Nitrogen content for each crop considered was drawn from a compilation by Lassaletta et al. (2014a).

It has been shown (Billen et al., 2013) that N leaching from arable land on average accounts for approximately 70% of the N surplus integrated over the crop rotation cycle, so that the knowledge of the mean infiltrated depth (110 mm yr^{-1} to 175 mm yr^{-1} in the Orgeval catchment) can estimate the sub-root nitrate concentrations.

3.2. Seneque-Riverstrahler model

The Riverstrahler model is a biogeochemical tool, describing in detail the in-stream processes affecting nutrients and aquatic microbial life and related water quality in a drainage network with the geomorphology of the basin, hydrology and climate (light, temperature), as well as the point and diffuse sources related to human activities. It is embedded in a Geographic Information System application (Seneque) (Ruelland et al., 2007). The Seneque/Riverstrahler outputs are concentrations of all variables taken into account in the RIVE model (including nutrients [N, P, Si, C], oxygen, bacteria, phyto- and zooplankton, suspended solids) in each river stretch of the drainage network. Fluxes as well as their ratios can also be calculated. The modeling tool has been implemented on several medium-large basins, more than 10,000 km^2, for temperate river basins of the North Atlantic façade (e.g., the Seine, Somme, Scheldt, Loire, etc.; Thieu et al., 2009; Passy et al., 2013), a monsoon basin in North Vietnam (the Red River, Le et al., 2014), and the continental Danube River (Garnier et al., 2002). Here it was adapted to a much finer spatial resolution for this catchment of ~100 km^2. The drainage network is considered in its entirety, differently from the description of sub-basins by Strahler stream-orders (cf. Billen et al., 1994). Fig. 4 shows the major constraints necessary for the implementation of the Riverstrahler model. In addition to the description of the drainage network and its elementary sub-basins, inputs as point and diffuse sources of any variable considered in the model must be documented. Regarding point sources, the three existing wastewater treatment plants are taken into account through their capacity and types of treatment (secondary, tertiary) in the Orgeval catchment. Diffuse sources are taken into account considering the sub-root concentrations calculated from the N surplus of arable and grassland, as explained above. For forested areas, a concentration of 0.35 mg N l^{-1} is considered, based on measurements of sub-root concentrations. Riparian retention is taken into account by considering, for each stretch of river, a temperature-dependent retention factor, which is proportional to the area of potential wetlands (Mérot et al., 2003) in the corresponding sub-catchment. The temperature dependence of retention (assumed to be denitrification) is taken from Benoit et al. (2015b). The relationship with potential wetland areas is calibrated by adjustment of the simulated results to the observed nitrate measurements at the basin outlet.

4. Results

4.1. Soil surface balance in current conventional and organic cropping systems

4.1.1. Conventional farming system

We used the ArSeine (Puech et al., 2014, 2015) and APOCA (Nicola et al., 2012; Schott et al., 2014) data bases to define a typical conventional crop rotation for the current agricultural system of the Orgeval basin, dominated by a crop succession such

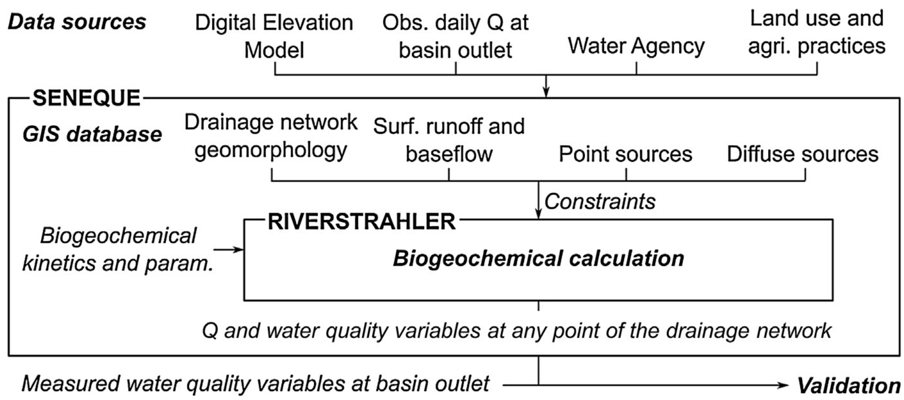

Fig. 4. Representation of the Seneque/RiverStrahler model, as fed by hydrology and morphology constraint data, land use and point sources. The Seneque GIS framework allows spatialization of these constraints. The biogeochemical Riverstrahler model calculates, using biogeochemical kinetics and parameters (param.), the concentrations of all water quality variables taken into account in the model, namely the nitrate concentrations of interest here (see Garnier et al., 2014).

as maize/wheat/faba bean or flax/wheat, for which the yield of each crop and the amount of mineral fertilization applied is provided in Table 1.

The major input comes from mineral fertilization (74%), whereas biological nitrogen fixation coming from faba bean represents only 13% and atmospheric deposition about 6% (Fig. 5a). Conventional farming uses exogenous organic fertilization for less than 10% (e.g., horse or cattle manure, beet vinasse, chicken droppings, etc.). The average harvest amounts to 169 kg N ha^{-1} yr^{-1}, for a N-SSB surplus of 30 kg N ha^{-1} yr^{-1} (the difference between total N inputs and total N outputs, Table 1). Taking into account an infiltration depth of 110–175 mm yr^{-1} as observed in the Orgeval catchment, this surplus corresponds to sub-root concentrations of 12–17 mg-N-NO_3 l^{-1}, in good agreement with the results of direct field measurements (Benoit et al., 2014, 2015b). The levels for conventional farming systems in the Orgeval catchment over 3 recent years ranged from 9 to 19 mgN/l (Benoit et al., accepted).

4.1.2. Organic farming system

In the region investigated, a typical organic rotation in the Orgeval catchment is characterized by a 8-year crop succession, alternating alfalfa/alfalfa/wheat/spring cereal/faba bean or lentil/wheat/spring cereal/flax. Two years with alfalfa as a starter crop of the rotation are intended to contribute enough N to the soil by symbiotic fixation to sustain the following cereal crops, as well as limit self-propagating weeds. Based on the information provided by farmers, we were able to document the amount of fertilization and the yield for each crop of the organic farming rotation (Table 1). Total fertilization in the organic farming system amounts to 148 kg N ha^{-1} yr^{-1},about 75% of the total fertilization inconventional farming systems, and biological nitrogen fixation accounts

Table 1
Representative soil surface balance (N-SSB, kg N ha^{-1} yr^{-1}) in the Orgeval catchment cropped in (a) a conventional farming system and (b) an organic farming system. Inputs: atmospheric deposition (Atm. dep.), exogenous mineral/organic fertilizers (Exog. min./org. fert.), biological nitrogen fixation (BNF) in kgN ha^{-1} yr^{-1}; outputs: yield in quintal ha^{-1} yr^{-1} (i.e., hundred kg ha^{-1} yr^{-1}), N content by crop (%) and crop yield in kgN ha^{-1} yr^{-1}. Inputs and outputs are the weighted average for the frequency of each crop in the rotation and summed up (total). Crop and forage yields are given separately. N-SSB is the difference between total inputs and total outputs (surplus).

(a) Conventional farming system

	Atm. dep. kgN ha^{-1} yr^{-1}	Exog. min. fert. kgN ha^{-1} yr^{-1}	BNF kgN ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Crop yield kgN ha^{-1} yr^{-1}	Forage yield kgN ha^{-1} yr^{-1}
Wheat (5/9)	11	194	0	83	1.8	149	
Maize (3/9)	11	166	0	111	1.8	200	
Faba bean (1/9)	11	15	214	51	3.5	179	
Inputs/outputs	11	165	24			169	
Total			199.6			169.5	
N-SSB			30.1				

(b) Organic farming system

	Atm. dep. kgN ha^{-1} yr^{-1}	Exog. org. fert. kgN ha^{-1} yr^{-1}	BNF kgN ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Crop yield kgN ha^{-1} yr^{-1}	Forage yield kgN ha^{-1} yr^{-1}
Alfalfa (1/8)	11		435	90	3.5		315
Alfalfa (1/8)	11		435	90	3.5		315
Wheat (1/8)	11	25		43	1.8	77	
Triticale (1/8)	11	25		43	1.8	77	
Faba bean (0.5/8)	11		147	35	3.5	123	
Lentil (0.5/8)	11		63	15	3.5	53	
Wheat (1/8)	11	25		43	1.8	77	
Cereal 2nd (1/8)	11	25		43	1.8	77	
Flax (1/8)	11	25		63	0.6	38	
Inputs/outputs	11	16	122			54	79
Total			148.4				133.1
N-SSB			15.3				

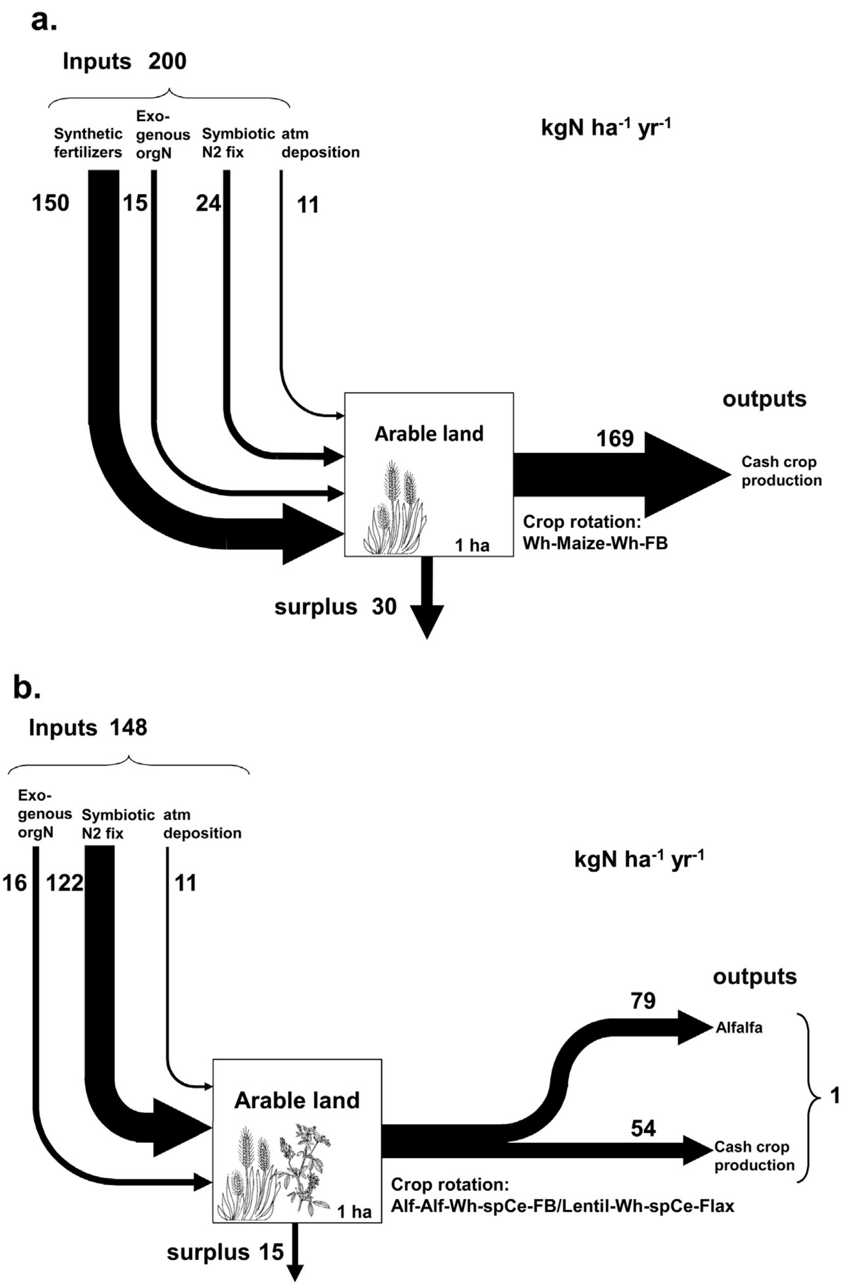

Fig. 5. Soil surface balance in $kgN\,ha^{-1}\,yr^{-1}$ in the Orgeval basin for (a) the current conventional farming system and (b) an organic farming system. Whereas (a) is characterized by a short rotation dominated by wheat (Wh) and maize, with faba bean (FB), (b) shows a long rotation with alfalfa (Alf), wheat (Wh), spring cereals (spCe), faba bean (FB) or lentil, followed by wheat (Wh), spring cereals (spCe) and flax. The difference between the inputs and outputs represents the N surplus.

for more than 80% of this, exogenous inputs (manure, organic residues from the food industry, etc.) making up less than 10% of the total N inputs. Atmospheric deposition represents 11% of total N inputs.

The amount of exported harvest is composed of 79 kg N ha^{-1} yr^{-1} alfalfa and 54 kg N ha^{-1} yr^{-1} cash crops, for a total of 133 kg N ha^{-1} yr^{-1}, a total production 21% lower than that of the conventional farming system.

The N-SSB surplus, estimated at 15 kg N ha^{-1} yr^{-1}, is half the value of the conventional farming system N-SSB surplus, mainly because of the reduction in total N inputs (Fig. 5b). The nitrogen use efficiency, defined as the amount of N harvested divided by the total N input to soils, is slightly higher in the organic (89%) than in the conventional system (84%).

With a similar depth of runoff (range, 110–175 mm), this surplus corresponds to sub-root concentrations from 6 to 9 mgN-$NO_3\,l^{-1}$, also in agreement with the direct measurements in organic farming parcels (Benoit et al., 2014, 2015a; Benoit et al., accepted).

A questionable aspect of the organic farming system is the large proportion of N production as forage legume (~60%) in the total production. The existence of a local outlet for alfalfa is therefore a crucial condition for the profitability of this type of organic farming. Although water extraction for a production of packed dried alfalfa for feed is a possible solution, the distance to collecting factories and the energetic cost of the dehydration process are often limiting factors for its feasibility.

4.2. Reconnecting cropping and cattle breeding

The rationale behind a reconnection must include agricultural multifunctionality, beyond pluriactivity, for which a collective effort between governments, producer and food processing networks, and consumers, is required to succeed in a real rural development option, reasserting the socio-ecological role of agriculture (Feenstra, 1997; Marsden and Sonnino, 2008). Many initiatives are in progress in the studied region, supported and moved by local elected officials, NGOs and Water Institutions. Despite a slow beginning in its use since its creation in 2001, the SCIC tool for partnership (Sociétés Coopératives d'Intérêt Collectif, set up by Act dated 17 July 2001, 2001-624) is now quickly swarming, thanks to new flexible amendments in 2007, 2012 and 2014. The willingness of farmers for changing their practices is also increasing.

Historically, the Brie region used to be an area of dairy and cheese production. Based on available statistical data for the year 1955, when permanent grassland area and dairy cow numbers were at a maximum, we reconstructed the biogeochemical functioning of the agricultural system of that time. Considering the same permanent grassland area (20% of the agricultural surfaces), we then explored a plausible scenario of modern reintroduction of livestock, following the current specification for organic cattle breeding, connected with the organic farming system described above for the remaining 80% of the utilized agricultural land. The N-SSB was calculated for this hypothetical modern system and for the past 1955-system.

4.2.1. N-SSB for the reconnected livestock organic farming system

Given that one main objective in designing the reconnected system is to allow full local use of forage legume production as cattle feed, we calibrated the herd on this basis, also meeting the specification of organic cattle farming requiring a maximum of two livestock units per hectare of permanent grassland. Per hectare of total agricultural area, the herd is thus made of 0.4 dairy cows and 0.3 heifers (half less than 1 year old, half 1–2 years old, i.e., 0.15 heifers1 ha^{-1} and 0.15 heifers2 ha^{-1}, respectively). The livestock is considered to graze (and excrete) for 7 months per year on grassland, with the remaining 5 months indoors, typical for this temperate region (Tables 2 and 3).

Grassland has a yield of 4 $tons_{dryweight}$ ha^{-1} yr^{-1} with 20% legume. With a N content of 2.5%, the 0.2 ha of grassland will produce 20 kg N yr^{-1}. The alfalfa produced by the 0.8 ha of cropland amounts to 63 kg N yr^{-1} (Table 1). To this, 5.3 kg N yr^{-1} of cereals complement the ration for the 0.3 heifers and 0.4 dairy cows (respectively, 0.08 tons and 0.24 tons of cereals per year with a N content of 1.8%), making a total feed consumption of 89 kg N ha^{-1} yr^{-1}, entirely produced within the farm (Table 3 and Fig. 6a).

In this type of system, with a milk production per head amounting to 6500 kg yr^{-1} (N content, 0.5%), the total milk production can be estimated at 13 kgN ha^{-1} yr^{-1}, to which meat production must be added. A reasonable assumption is that half of the calves are sold at a weight of 100 kg, leaving the second half for replacement of dairy cows, sold after 3 years lactation at a weight of 600 kg. Considering an average of 1.3% for the N content for whole animals, meat production is evaluated at 1.5 kg N ha^{-1} yr^{-1}, much less than milk production. These figures, leading to 84% excretion and a conversion ratio of 16% from vegetal to animal protein, fit well with those generally provided (Stouman Jensen and Schjoerring, 2011).

Of the excreta produced, 30% is considered to be lost by volatilization (Oenema et al., 2007); 40% of the remainder is assumed to be directly deposited on grassland during grazing time (7 months per year) while the rest is assumed to be produced indoors and applied on cropland (Table 2).

The total N inputs to cropland are dominated by biological nitrogen fixation (76%), followed by manure (17%) and atmospheric deposition (7%). For grassland, the N inputs come from direct excretion (75%), symbiotic fixation (20%), and atmospheric deposition (5%).

Because of slightly higher fertilization, the overall yield of the different crops in the reconnected cropping system is also higher than the specialized organic cropping system, assuming that the same yield–fertilization relationship is achieved, although some results show a better performance for livestock-organic farming systems (Anglade et al., 2015a). We assumed that this would imply a 25% increase yield in the non-legume crops, whereas the legume yields are not affected. As a result, exported cash crop production for a livestock organic farming system, is only 8.5% lower than for an organic cropping system and compensated by substantial exported animal production, while alfalfa can find a local outlet (Fig. 6a).

As a whole, the surplus obtained for arable land in this reconnected organic system is 13 kg N yr^{-1} for 0.8 ha, i.e., 16 kg N ha^{-1} yr^{-1}, close to the surplus obtained for the organic cropping system of 15 kg N ha^{-1} yr^{-1}, whereas the grassland surplus (18 kg N yr^{-1} for 0.2 ha, i.e., 90 kg N ha^{-1} yr^{-1}) is below the threshold of 100 kg N ha^{-1} yr^{-1} above which significant N leaching occurs (Billen et al., 2013).

4.2.2. N-SSB in the Orgeval catchment in 1955

From the 1955 agricultural statistics, we assumed four crops – alfalfa/wheat/beetroot/spring cereal – equally distributed over the 80% of arable land while 20% of agricultural land was permanent grassland. One-third of the beetroot production is fed to livestock (Tables 2 and 3). Grassland yield is 3.5 $tons_{dryweight}$ ha^{-1} yr^{-1}, corresponding to 18 kg N yr^{-1} for 0.2 ha of grassland, with the same assumption as above.

According to the statistics, the livestock was composed of 0.2 dairy cows and 0.2 heifers ha^{-1} (0.1 heifers less than 1 year old, 0.1 from 1 to 2 years old among which 0.05 for cull cow renewal). Moreover, 0.28 head of sheep and the 0.11 head of pig per hectare added to the diversity of livestock at that time. Livestock was again considered to graze (and excrete) for 7 months per year on grassland, with the remaining 5 months indoors.

Milk production per head was about 2500 kg yr^{-1} (N content, 0.5%), leading to a milk production of 2.5 kg N ha^{-1} yr^{-1}, to which a total of 1 kg N ha^{-1} yr^{-1} of meat production must be added. The availability of feed totals 64 kg N ha^{-1} yr^{-1} (18 kg N ha^{-1} yr^{-1} from grassland, 42 kg N ha^{-1} yr^{-1} from alfalfa, and 4 kg N ha^{-1} yr^{-1} from beetroot) (Table 3). Excretion therefore totals 60 kg N ha^{-1} yr^{-1}, including 18 kg N ha^{-1} yr^{-1} as manure on cropland and 25 kg N ha^{-1} yr^{-1} as direct dejection on grassland after a 30% removal due to volatilization (Table 3 and Fig. 6b). These figures lead to a 6% conversion ratio from vegetal to animal protein, a value approximately 2.5 times lower in 1955 than the values estimated presently.

Besides exogenous organic fertilizers from livestock, biological nitrogen fixation amounts to 63 kgN.ha^{-1}.yr^{-1} (5 kg N ha^{-1} yr^{-1} from the 20% legumes in 0.2 ha of grassland and 58 kg N ha^{-1} yr^{-1} related to one-quarter alfalfa among the four dominant crops of the rotation on 0.8 ha of cropland). According to the agricultural statistics, synthetic fertilizers were applied on cereal crops at a rate of 35 kg N ha^{-1} yr^{-1}, making an input of 14 kg N yr^{-1} per 0.8.ha for the crop distribution as taken in 1955 (Fig. 6b).

Regarding atmospheric deposition, we estimated a value of 7.3 kg N ha^{-1} yr^{-1} instead of 11 kg N ha^{-1} yr^{-1} for the present, considering the trends described by Ruoho-Airola et al. (2012) and Asman and Drukker (1988), namely a 60% decrease since the 1980s and a 40% increase between 1955 and 1980.

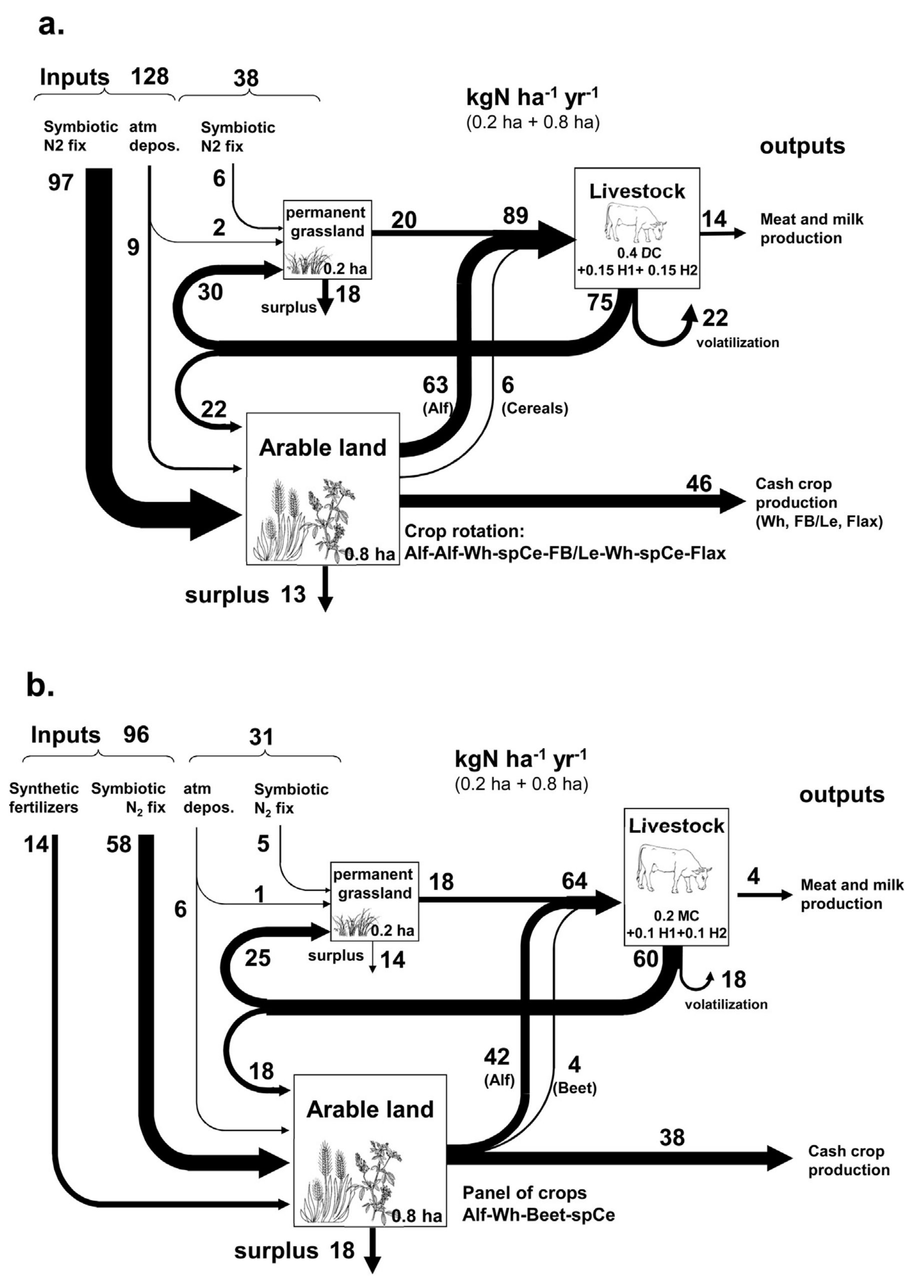

Fig. 6. Soil surface balance in kgN ha^{-1} yr^{-1} in the Orgeval basin (a) for the organic farming system (see Fig. 5) reconnected with livestock (see Table 3) and (b) for the situation in 1955 with a panel of crops characterized by alfalfa (Alf), wheat (Wh), beetroot (Beet) and spring cereals (spCe) equally distributed on arable land. Livestock is introduced according to the organic farming specification (a) and 1995 agricultural statistics (b). The difference between the inputs and outputs represents the N surplus.

The overall N budget of the 1955 livestock-cropping system is thus established as shown in Fig. 6b. The N surplus on cropland is estimated at 22.5 kg N ha^{-1} yr^{-1}, corresponding to a nitrate sub-root concentration in the 9–13 mg N l^{-1} range. Per hectare of agricultural land, the cash crop yield amounts to 38 kg N yr^{-1}, while animal products are about 3.5 kg N yr^{-1} (Fig. 6b).

It should be noted that a high number of horses in the 1950s were replaced by tractors in the 1970s. Besides dairy cows and heifers, the number of pigs, sheep, and goats was also rather high at the middle of the last century (see Fig. 2).

4.3. Modeling nitrate contamination in the river

Once the model has been implemented and calibrated, the simulations by the Riverstrahler model with the constraints corresponding to the conditions of the present conventional farming practices can be compared to the observed nitrate concentrations for validation. The station at the catchment outlet (le Theil) is shown (Fig. 7). A strong seasonal variation is observed in discharge values, as well as in nitrate concentrations, which are in good agreement with the simulations. This good agreement with the observed concentrations in nitrate over the past 10 years, including wet and dry years, and their modeled seasonal variations, tend to show that (i) the diffuse and point sources are adequately taken into account and (ii) the processes describing N transformation are well represented.

Observed nitrate concentrations range from 5 to 16 mg N-NO_3 l^{-1}, averaging 10.3 mg N-NO_3 l^{-1}, comparing well with the simulated average of 10.7 mg N-NO_3 l^{-1} (Fig. 7). Various validation indexes were calculated for nitrate. The RMSE (root mean square

Table 2
Soil surface balance (N-SSB, kgN.ha^{-1}.yr^{-1}) in the Orgeval catchment, for (a) the reconnected livestock-organic crop farming system and (b) the 1955 historical situation. We consider that for 1 ha farming area, 0.8 ha is devoted to cropland, whereas 0.2 ha is assigned to permanent grassland for livestock breeding. Inputs for the 0.8 ha of cropland (i, iii) and 0.2 ha of grassland (ii, iv): atmospheric deposition (Atm. dep.), manure (produced at the farm scale replaces exog. min./org. fert.), biological nitrogen fixation (BNF) in kgN.ha^{-1}.yr^{-1}; outputs: yield in quintal ha^{-1} yr^{-1} (i.e., hundred kg ha^{-1} yr^{-1}), N content by crop (%) and crop yield in kgN.ha^{-1}.yr^{-1}. Cash crop and forage yields are given separately. Inputs and outputs are weighted average for the frequency of each crop in the rotation and summed up (total). N-SSBs, the differences between total inputs and total outputs (surplus), are calculated separately for cropland and grassland. Livestock manure (excretion) represents the difference between ingestion and production minus 30% volatilization and is split on grassland and cropland according to the time spent outdoors (7 months) and indoors (5 months).

(a) Reconnected livestock- organic crop farming system

(i) 80% crop land

	Atm. dep. kgN 0.8 ha^{-1} yr^{-1}	Manure kgN 0.8 ha^{-1} yr^{-1}	BNF kgN 0.8 ha^{-1} yr^{-1}	Min. fert kgN 0.8 ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Crop yield kgN ha^{-1} yr^{-1}	Forage yield kgN ha^{-1} yr^{-1}	Yield kgN 0.8 ha^{-1} yr^{-1}
Alfalfa (1/8)	8.8		348		90	3.5		315	252
Alfalfa (1/8)	8.8		348		90	3.5		315	252
Wheat (1/8)	8.8				54	1.8	97		77
Triticale (1/8)	8.8				54	1.8	97		77
Faba bean (0.5/8)	8.8		118		35	3.5	123		98
Lentil (0.5/8)	8.8		50		15	3.5	53		42
Wheat (1/8)	8.8				54	1.8	97		77
Cereal 2nd (1/8)	8.8				54	1.8	97		77
Flax (1/8)	8.8				79	0.6	47		38
Inputs/outputs	8.8	22	97	0					
Total				127.9					115.2
N-SSB				12.7					

(ii) 20% grassland (80% grass family, 20% legume)

	Atm. dep. kgN 0.2 ha^{-1} yr^{-1}	Manure kgN 0.2 ha^{-1} yr^{-1}	BNF kgN 0.2 ha^{-1} yr^{-1}	Min. fert kgN 0.2 ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Grass yield kgN ha^{-1} yr^{-1}	Leg. yield kgN ha^{-1} yr^{-1}	Yield kgN 0.2 ha^{-1} yr^{-1}
Inputs/outputs	2	30	5.5	0	40	2.5	80	20	20
Total				38.1					20
N-SSB				18.1					

(b) 1955

(iii) 80% crop land

	Atm. dep. kgN 0.8 ha^{-1} yr^{-1}	Manure kgN 0.8 ha^{-1} yr^{-1}	BNF kgN 0.8 ha^{-1} yr^{-1}	Min. fert kgN 0.8 ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Crop yield kgN ha^{-1} yr^{-1}	Forage yield kgN ha^{-1} yr^{-1}	Yield kgN 0.8 ha^{-1} yr^{-1}
Alfalfa	6		232		60	3.5		210	168
Wheat	6			28	32	1.9	61		49
Barley	6			28	27	1.8	49		39
Beetroot	6				335	0.2	67		54
Inputs/outputs	6	18	58	14					77
Total				95.4					
N-SSB				18.2					

(iv) 20% grassland (80% grass family, 20% legume)

	Atm. dep. kgN 0.2 ha^{-1} yr^{-1}	Manure kgN 0.2 ha^{-1} yr^{-1}	BNF kgN 0.2 ha^{-1} yr^{-1}	Min. fert kgN 0.2 ha^{-1} yr^{-1}	Yield quintal ha^{-1} yr^{-1}	N content %	Grass yield kgN ha^{-1} yr^{-1}	Leg. yield kgN ha^{-1} yr^{-1}	Yield kgN 0.2 ha^{-1} yr^{-1}
Inputs/outputs	1	25	5	0	35	2.5	70	18	18
Total				31.0					17.5
N-SSB				13.5					

error) of 2.03 mg N-NO_3 l^{-1} means a 20% error compared to the average, whereas the two other dimensionless indexes provide an even better evaluation, taking into account the large number of observations (1600), the Bravais-Pearson correlation reaching 0.46 and the reformulated Index Of Agreement (IOA) as high as 0.61 (Willmott et al., 2012).

To explore the effect of a change in agricultural practices, the model was run for the conditions corresponding to (i) the specialized organic cropping system and (ii) the simulated reconnected organic livestock and cropping system as described above. The results show a notable decrease of nitrate concentrations (close to 50%) in the river's surface water at the catchment outlet for both scenarios compared to the present conventional farming situation (Fig. 7). In spite of a similar N surplus (per ha) of arable land in the reconnected livestock cropping system, water quality was nevertheless slightly better (9% less in average nitrate concentrations) than in the specialized organic farming system due to the presence of 20% permanent grassland not subjected to high nitrate leaching.

The model was also run for the conditions corresponding to the 1955 situation. The mean nitrate concentration was 35% lower than that of the conventional farming systems. However, the 1955 system showed lower performance in terms of yields than the organic farming system as simulated here, whether or not it was reconnected.

Table 3
Livestock description for a reconnected livestock-organic crop farming system (Reconn. Org. F), designed for 1 ha with 0.4 dairy cows, 0.15 heifers <1 year old and 0.15 heifers 1–2 years old for livestock renewal. Comparison with the 1955 situation comprising 0.2 dairy cows, 0.10 heifers <1 year old and 0.10 heifers 1–2 years old (among which 0.05 for dairy herd renewal). In 1995 statistics indicate in addition 0.11 pigs and 0.28 sheep per ha.

	Reconn. Org F kgN yr^{-1}	1955 kgN yr^{-1}
Ingestion		
Grassland	20.0	17.5
Alfalfa	63.0	42.0
Feed supplement	5.8	4.4
Total	***88.8***	***63.9***
Production		
Milk	13.0	2.5
Bovine meat	1.5	0.7
Pig meat	–	0.1
Sheep/goat meat	–	0.2
Total	***14.5***	***3.5***
Animal excretion		
Volatilization	22.3	18.1
Manure	21.7	17.6
Direct dejection	30.3	24.7
Total	***74.3***	***60.4***

Ingestion: grassland and alfalfa yield are entirely used for livestock feeding to which 0.32 tons of cereals (with a N content of 1.8%) are added to the ration (0.08 tons to the 0.3 heifers and 0.24 tons to the 0.4 dairy cows). In 1955, 1/3 of the beetroot production was fed to the livestock.
Production: milk production is taken at 6500 kg $DC^{-1} yr^{-1}$ for the present reconnected livestock-organic crop farming system, with a N content of 0.05%. Meat production corresponds to 0.15 young heifers (150 kg) and 0.15 DC (600 kg to be renewed), N content of the meat being 1.3%. For 1955 milk production is considered to be 2500 kg $DC^{-1} yr^{-1}$ and yearly meat production comprises 0.05 DC (500 kg), 0.1 young heifers (150 kg), plus 0.05 1- to 2- year-old heifers (250 kg) to which 0.011 pigs (100 kg) and 0.028 sheep (50 kg) is added.
Animal excretion: total excretion is calculated as ingestion minus production. Volatilization is 30% of the total, with the rest distributed according to the time spent outdoors (7 months) and indoors (5 months) (see Table 2).

5. Discussion

The shift from manure-based to synthetic N fertilization in the early 1950s made possible a strong regional specialization of agriculture throughout Europe, with exclusive crop farming in fertile lowlands, such as in the Paris Basin, and livestock farming strongly dependent on imported feed in other regions such as Brittany (Billen et al., 2012). Whereas the Seine Basin exports 80% of its cereal production to northern Europe, Maghreb, and the Middle East, it imports most of its animal proteins from the North and West of France, two regions that import approximately 30% of their feed from South America (Le Noë et al., 2016). With rather low-cost synthetic fertilizers, specialization and intensification have led to substantial reduction of the nitrogen use efficiency (Lantinga et al., 2013; Lassaletta et al., 2014b), hence to high N losses to the environment, causing detrimental ground- and surface water N contamination and atmospheric pollution (NH_3, N_2O). Despite national and European directives, the increasing trend of water nitrate concentrations has not yet been turned around, but at best the concentrations have stabilized, although at levels too high to meet the standards of drinking water production. Indeed, 400 wells have been abandoned in the last 10 years in the Seine basin because of excess nitrate and/or pesticide levels (Direction Générale de la Santé, 2012).

The Orgeval catchment in the Seine Basin is a typical case study of intensive agriculture where livestock production has been removed from cropping systems, and where the water agency and drinking water producers are supporting field experiments with farmers and researchers to protect water resources. With the knowledge gained on the Orgeval catchment (Garnier et al., 2014) and the collaboration engaged with farmers (Nicola et al., 2012; Anglade et al., 2015b; Benoit et al., 2015a), exploring agriculture changes and encouraging consensus in terms of sustainability of production systems (here organic cropping systems and organic livestock production systems) is particularly relevant.

A main challenge would be a re-thinking of the livestock production system for being attractive to young farmers and overcoming the hard work or long daily hour constraints of taking care of the animals. This must lead to re-design the farm work and to organize educational programmes for farmers, issues to be addressed through organic farming policies together with consumer information, domestic market development, etc. (Stolze and Lampkin, 2009).

This change should lead to new organization of the farm work (with small-scale milk-processing plants for its diversification and ensuring incomes) and new organization of livestock and crop production at the territorial scale. This means the re-creation of a milk network (collection and transformation of milk, milk inspection, veterinary medicine) which has disappeared from the region specialized in crop farming. New articulations between rural and urban areas must be found and local consumption via alternative food network should be also promoted and facilitated (Feenstra, 1997). Further, the National Federation of Organic Agriculture (FNAB: http://www.fnab.org) currently coordinates since 2007 a multi-stakeholder working group for collective actions in food supply chains, territorial development, and public policy-building so that these products are available at a reasonable price while ensuring farmer incomes. Analysing local organic food networks, Seyfang (2006) advocates that the growth of ecological citizenship is a powerful motivating force for sustainable consumption behavior.

5.1. Organic cropping system and soils

Compared to current conventional agriculture in the Orgeval catchment, the organic rotations as applied in this region, i.e., beginning by 2–3 years alfalfa with an alternation of cash crop and legumes for the following 5–8 years, typically increase not only crop diversity, but also the soil's biological diversity (Altieri, 1999; Bengtsson et al., 2005). In addition, the important role played by long rotations in improving soil structure (Havlin et al., 1990), soil organic C sequestration (Plaza-Bonilla et al., 2015a), efficient nutrient cycling, and combined use of C, N, and P has been clearly established (Lemaire et al., 2014; Blesh and Drinkwater, 2013). Furthermore, diversified rotations, especially those including alfalfa (Bellinder et al., 2004), have been shown to efficiently control weed communities and disease populations (Stockdale et al., 2001), so that the use of pesticides can be avoided or at least considerably reduced. This is typically a lesson taken by organic systems that completely banish the use of pesticides in their specification (Council Regulation N°834/2007) in addition to beneficial use of biological nitrogen fixation for fertilization. Indeed, exogenous organic inputs (such as manure, vinasse, hens dropping, etc.) account for only 10% of the total fertilization in the typical organic cropping systems in the Orgeval catchment, compared with the conventional systems where exogenous synthetic fertilizers account for 80% and total N inputs to soil is 25% higher. Interestingly, the lower total fertilization rate in organic systems is not reflected in a proportionally lower yield when expressed in N compared to conventional systems (90% less exogenous fertilization vs. 21% lower yield), and the N surplus of arable land is reduced by 50%, leading to a reduction of nitrate concentration below the drinking water standard of 11.3 mg N l^{-1} in infiltrating water and surface water.

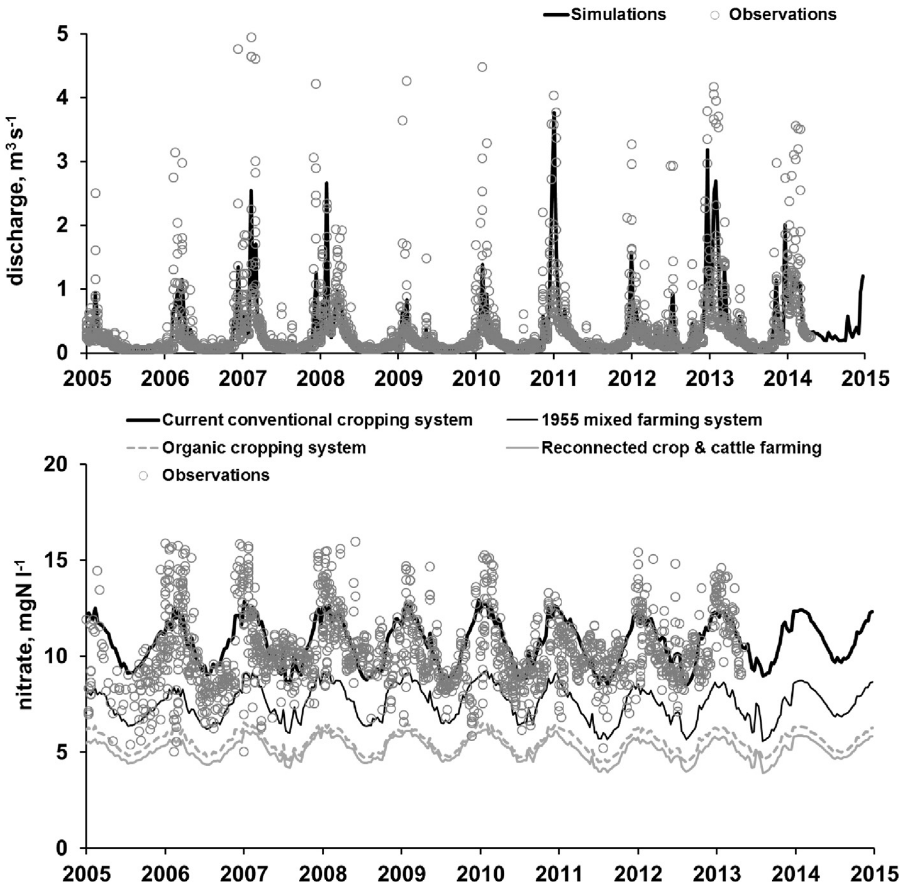

Fig. 7. (a) Seasonal variations of the discharge values at the outlet of the Orgeval catchment from 2005 to 2015 (calculations after discretization computed using the Eckhardt recursive filter (Eckhardt, 2008) applied to discharge data at different gauging stations are compared to the observations). (b) Seasonal variations of (i) the simulations by the Seneque/RiverStrahler model of nitrate concentrations for the current situation compared with observations (data from Tallec et al., 2015) (ii) simulations for the situation in 1955 and for (iii) situations of structural changes in agriculture, e.g., organic farming systems and reconnected livestock to organic farming systems.

By reducing the period when soils are bare, the introduction of cover crops within a rotation can further limit N leaching (Meisinger et al., 1991; Justes et al., 2012; Benoit et al., 2014; Benoit et al., accepted; Plaza-Bonilla et al., 2015b). Despite the recent regulation for a systematic use of cover crops (in 2012) in the whole Seine basin, cover crops are still rarely implanted and not taken into account in our calculations in either the organic farming or conventional farming system. Such a still low implementation of cover crops might be due to (i) the time-lag for the farmers to adapt their working activity (ii) the authorization for exemption and (iii) the lack of communication to the farmers on the efficiency of this measure in terms of leaching reduction. Therefore, further beneficial effects on water nitrate contamination can be expected.

5.2. Livestock breeding and grassland

The main barrier preventing the generalization of organic cropping practices in the Seine basin and the Orgeval catchment is the lack of a local outlet for the production of alfalfa or other forage legumes. Another issue is the lack of structuration of the organic milk sector. Today, organic milk collectors are absent from the Ile-de-France region, so that, isolated organics farms are forced to sell the major part of their organic milk as conventionally produced milk, at a clearly unprofitable level in view of the constraints involved in the production. The adding value generally comes from a minor part of the milk production, transformed in cheese, directly sold at farm gate, in farmers market or by the AMAP network (a consumer network to assist small local farmers using organic agriculture, http://www.amap-idf.org/). However, catering sectors are real opportunity for locally structuring innovative agro-food systems. School catering which falls within the competences of local elected officials can be an efficient lever for supporting local production of animal products (e.g., yoghurt for which a huge potential outlet exists for the Parisian region of 12 million people). Further Paris Megacity is a touristic place where cheese, including the Brie one, remains a high-demanded product as both a traditional and local country food. Regarding meat, the supply of organic one is not yet developed at all. A real political will is therefore necessary for an economically viable transition (Reganold and Wachter, 2016). Exploring a scenario reconnecting crop and animal production not only follows the lines of the European organic farming regulation (Council Regulation N°834/2007) but meets a demand.

In addition to consuming locally produced alfalfa, in our scenario livestock is also assumed to feed on grassland, considered to be important for sustainable animal production and to balance damage caused by intensive crop production (Lemaire et al., 2014).

The moderate livestock density (0.54 livestock unit per hectare of farmland, with grassland covering 20% of utilized agricultural land, as was the case in 1955) also allows direct fertilization of grassland as well as manure fertilization of cropland. We assumed that 30% of animal excretion is lost, especially from NH_3 volatilization (Oenema et al., 2007). Although this proportion may be overestimated when animals are grazing (Lantinga et al., 2013), more could be lost (50%) during manure collection, handling, and land application (Tomich et al., 2011), confirming the value of 30% used here. Far from being a waste disposal problem, manure management and nutrient recycling of animal excreta (Tomich et al., 2011), made possible through reconnection with crop farming, allows farms to reach a high level of autonomy.

The regional specialization of agriculture into either livestock or crop farming during the last 50 years has greatly increased livestock production in response to an increasing demand for animal protein, following both population growth and per capita consumption (Billen et al., 2013; Lassaletta et al., 2014b; Garnier et al., 2015; Lemaire et al., 2014). Paris agglomeration, the largest French consumption basin, imports its animal products from other specialized area, such as Brittany in France (Le Noë et al., 2016). This is the cause of severe threats, as recently shown at the European scale by Leip et al. (2015), who estimated that industrial livestock farming accounts for a large part of environmental damage stemming from agriculture, including water and air quality, biodiversity loss, and climate change. For this reason, a reduction of the proportion of animal protein in the human diet, toward a value of around 40% of the total protein intake, has been proposed as a useful objective in developed countries, for public health reasons as well as for environmental and equity concerns (Billen et al., 2015; Westhoek et al., 2014).

The scenario explored herein for the Brie region is completely in line with these recommendations. The livestock density based on 0.7 head ha^{-1} farmland is indeed moderate. In terms of human food produced, higher consumption of vegetal protein is beneficial, due to the ratio of vegetal to animal protein conversion of about 30%, at best. The crop rotation proposed also leaves room for some non-food production (flax in our example). Therefore, in agreement with Lemaire et al. (2014), a reconnection might not cause competition with human food. Our scenario of reconnected organic farming systems does not greatly modify the N-SSB (as a N leaching indicator) obtained for organic cropping, but the major challenge, i.e., a local utilization of alfalfa, is met. This scenario could be modulated by a diversification of alfalfa outlets such as biogas production (Solagro, 2014) or dehydration. We did not estimate the possible difference in terms of greenhouse gas emission, but taking into account previous investigations on N_2O and CH_4, at the catchment scale a possible increase in CH_4 would match a N_2O decrease (Benoit et al., 2015a; Garnier et al., 2009, 2013; Vilain et al., 2012). Indeed CH_4 and N_2O contribute to the same emission bill and can be considered comparable after correction by their respective global warming potential.

For 1955, the N-SSB is about 40% higher than that of the reconnected organic farming system, but more than 20% lower than the present conventional system. This means that the organic farming system we described here is by no way a return to the 1955 system, but represents the result of structural changes bringing better performance stemming from innovative practices, benefiting from new technology and agronomical knowledge; it could only be generalized owing to cooperation among farmers and with the stakeholders of the agro-food system and consumer demand (Bell et al., 2014; Lemaire et al., 2014).

Cash crop production is close for both specialized and reconnected organic systems, the small amount of cereal production devoted to complement cattle ration in the livestock system being compensated by a yield increase based on manure application. In 1955 beetroot, an important component in the crop rotation, was also used to a large extent as a feed complement to pasture grazing and alfalfa (Table 3). In the 1955 system, whereas cash crop production was only 17% lower, animal production appears much lower than in our simulated livestock organic farming system, designed here with more milk than meat production. This difference, *de facto* more due to milk than meat production (Table 3), results from both the lower number of dairy cows (0.4 dairy cows per ha in the reconnected organic farming system *vs.* 0.2 dairy cows per ha in 1955) and the lower milk productivity (6500 kg yr^{-1} per dairy cow for present reconnected organic farming system vs. 2500 kg yr^{-1} per dairy cow for 1955), with identical protein content (0.5% N) in both cases. The hypothesis used for designing the scenario of reconnected organic farming system increased the efficiency in vegetal-to-animal conversion from 6% in the 1950s to 16% today. It must be mentioned, however, that because the reconnected organic farming system scenario studied is based on a N point of view, N in the animal diet could exceed energy need, especially from alfalfa, possibly leading to an underestimation of NH_3 volatilization. Therefore, reducing livestock or increasing grassland in the crop rotation of the reconnected organic farming system would probably allow a better animal diet equilibrium by reducing the proportion of alfalfa.

As a whole, an extensification of animal production and its reconnection with cropping systems would not greatly further decrease N leaching from soils with respect to specialized organic farming systems, but, by providing a direct outlet for legume fodder crops, would make organic farming more economically sustainable on a large scale. In addition, regular animal manure application to soils would improve long-term soil fertility (Tilman, 1998) and reduce the risk of a phosphorus (and potassium) shortage in soils, a major threat for organic cropping systems, as suggested by Lantinga et al. (2013) and Nowak et al. (2013). Moreover, the reintroduction of livestock in regions specialized in crop farming will also allow a de-intensification of livestock breeding in other regions, thus resulting in better management and recycling of animal manure, and reducing N diffuse polluting sources to water masses, as well as gas emission and volatilization at multiregional or even national scales (Hacker et al., 2009). In other words, the approach discussed herein has not estimated the N pollution produced in the conventional system outside of the basin studied that would be avoided with the reconnected livestock production system. This “external pollution” is more or less important depending on the degree to which the livestock systems depending on imported cash crops for feed are intensified and on the legislation and manure application ceilings.

Whereas organic cropping systems reduce the dependence of farmers on chemical mineral fertilizers and pesticides, which are largely fossil energy-dependent, livestock reconnection to cropping would obviate the need for using limited mining resources (e.g., phosphorus), contributing to a sustainable agriculture in the future relying on natural sources (Rigby and Cáceres, 2001; Tomich et al., 2011; Lemaire et al., 2014; Garnier et al., 2015).

5.3. Agriculture and water quality

In the framework of the EU-WFD (2000), European countries, including France, aimed at reaching a good chemical and biological status of their water masses for the year 2015. However whereas treatment of domestic and industrial wastewaters have been considerably improved in the French wastewater treatment plants (Romero et al., 2016), the poor implementation of the EU-Nitrate Directive (1991) to protect surface and groundwater from agricultural nitrogen pollution, has led French authorities to be convicted by the European Court of Justice. Nevertheless, Anglade et al. (2015a) have shown that the latest French application of the EU Nitrate Directive, mainly based on achieving a balanced mineral fertilization giving objective yields, is already widely applied in the Seine watershed and N surpluses remain too high to prevent water contamination. Therefore, on the basis of a success story such as the city of Munich, which as soon as 1991 encouraged farmers to organic agriculture in the drinking water catchment area of the city (http://www.partagedeseaux.info/Munich-Promoting-organic-agriculture-to-avoid-treating-water), several actions are being implemented at the scale of French selected territories, to recover and/or protect water quality by promoting organic farming practices."Eau et Bio" (http://www.eauetbio.org/) is one of such action programmes already concerning a dozen of territories, and as many are foreseen. "Eau de Paris", a public operator in charge of the production and distribution of drinking water to Paris, has already extended these actions in a catchment close to the Orgeval one by strategically strengthening their presence with field facilitators, providing conversion aid toward organic farming systems (up to 450 euros ha^{-1}).

Our results confirm the relevance and appropriateness of such policies. When running the scenario structurally modifying the current conventional farming systems to the organic ones (reconnected with livestock or not, i.e., a surplus of $\approx$ 15 kg N-NO_3 ha^{-1}), an abatement of nitrate concentrations by a factor about 50% in surface water is simulated, leading to values compatible with the standard for drinking-water production. Organic agriculture would thus allow reconciling innovative high-performance agriculture and good water quality as it used to be in the 1950s before the massive use of fertilizers and pesticides. Interestingly, the reconnected organic livestock and crop farming system would not worsen water quality compared to the one in organic cropping, despite the rather high amount of manure production, especially because of the buffer effect of grassland which, owing to its permanent vegetal cover, resist N leaching when appropriately managed (Scherer-Lorenzen et al., 2003; Vertès et al., 2007).

Finally, the emission of N compounds to the environment in the EU produces significant external costs, a significant burden for society. Agricultural systems that reduce N pollution while simultaneously producing sufficient agricultural yields and demanding lower inputs help bridge the gap between farming and the needs of today's society (van Grinsven et al., 2013, 2015; Hennart et al., 2013).

6. Conclusion

This study shows that conventional systems and present practices, based on short crop rotation with chemical fertilization, cannot meet today's water-quality standard. Organic farming systems, with long and diversified crop rotation, including alfalfa as a starter crop of the rotation and alternating cereal and grain legume, can reduce by half nitrogen losses in surface water and, are as efficient in terms of N yield as conventional systems. The 21% decrease in N protein exported by organic rotations corresponds to 26% lower soil N inputs, with exogenous inputs representing only 11% of total N imports to the soil. In the present context, the few organic farmers have outlet opportunities for their production of alfalfa, which accounts for a large proportion of total N production. Despite the lower cereal yield of these systems, farmer's net income is not reduced because their expenses are much lowered owing to the suppression of pesticides and the reduced recourse to exogenous fertilizers (ABAC Network of Farmers, pers. comm.). However a generalization of organic farming and associated alfalfa production would not stand without a local outlet for this production, and an extension of the local offer of manure (Nowak et al., 2013). Furthermore, all of them consider their work more agronomically interesting, with more autonomy with regards to the decision-making process and the need of exogenous resources. In addition to these individual benefits for farmers, the services provided as water quality improvement must also be included (Good and Beatty, 2011).

The reconnection of organic crop farming with livestock breeding makes possible to consume locally the large legume forage production inherent to this cropping system, while maintaining a good water quality. It is therefore time to free agriculture from this unsustainable paradigm of adding large amounts of synthetic fertilizers to support food and feed production, while considering manure as a waste (Tomich et al., 2011).

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