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Integrated crop and livestock systems in Western Europe and South America: A review

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ABSTRACT

For many years, we have seen an increasing specialization of agricultural systems and territories, with a clear separation between territories with very high animal densities and those devoted to the growing of annual crops. This development is explained by market and sector economic logic and has been reinforced by the availability of low-cost inputs and animal housing systems based on direct grazing not requiring straw. It has, however, also involved negative environmental impacts and, in some cases, the impoverishment of soil fertility, a loss of biodiversity, and excesses of N and P, leading to eutrophication and hot spots of ammonia emission in livestock-breeding territories. Having recapped the mechanisms behind the specialization of systems and territories, we examined the extent to which the development of innovative mixed-farming systems that reconnect livestock and crop production on various territorial scales (farm, district, region) can reduce the negative impacts of agriculture on the environment, produce valuable ecosystem services and achieve acceptable economic efficiency for farming enterprises. Examples from temperate regions will be used to show that mixed-farming systems increase the possibilities of better recycling of nutrients within systems, limiting recourse to the purchase of increasingly expensive inputs and safeguarding the biodiversity of agricultural ecosystems.

1. Introduction

In response to increased market demand and economic pressures, agricultural systems and territories have become increasingly specialized (Clothier et al., 2008). The productivity of the agricultural sector has greatly increased and mixed-farming systems integrating crop and livestock production have strongly declined in many countries or regions. These changes have been greatly favoured by an era of cheap energy, which has encouraged high inputs of fertilizers and pesticides and the development of animal housing systems that do not need cereal straw. During this period, the negative impacts of agriculture on the environment have been largely ignored. In 2007, 52% of European holdings were specialized in cropping (20% annual crops, 22% perennial crops and horticulture, and 12% mixed crops), while 34% of holdings were specialized in livestock breeding (17% ruminants, 5% monogastrics and 12% with mixed types of animals). Only 14% of holdings are now mixed farms with both livestock and crops (Eurostat, 2010a,b). Some territories are highly specialized in animal production (West of France, Netherlands, Denmark, Po Valley), while other are specialized in crop production (South West and Central France, East of England, East Germany). Specialization has also occurred in Argentina. Most livestock farming takes place in the flood prone Pampa sub-region, a scarcely cultivated area having from 240 to 830 thousand head of livestock per county, mostly beef cattle, while the highest cropping intensity is found in the Rolling Pampa sub-region, where soybean (*Glycine max* L. Merrill) and maize (*Zea mays* L.) are predominant. Despite the predominance of cropping, the Rolling Pampa can be subdivided in an eastern part, with as few as 2–140 thousand head of livestock per county, and a western part, with 140–440 thousand of head of livestock per county (Ministerio de Agricultura, Ganadería y Pesca, 2012).

Highly intensive and specialized livestock production systems and a landscape dominated by intensive cropping have both contributed to environmental degradation. Specialized livestock systems and territories face problems of waste disposal leading to nutrient accumulation in the soil (P) and emissions of N to water and air. Meanwhile, territories specialized in crop-growing face soil

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impoverishment and have to import mineral fertilizer and pesticides. It would appear that conservation-oriented mixed-farming systems can maintain high levels of productivity while using N more efficiently, and can offer solutions that alleviate environmental damage (Donaghy et al., 1997; Oomen et al., 1998). After recapping the mechanisms behind the specialization of systems and territories, in this paper we shall examine the consequences of specialization and intensification. We shall then analyze the extent to which the development of conservation-oriented mixed-farming systems that reconnect livestock farming and crop production on various territorial scales can achieve acceptable economic efficiency on the part of farming enterprises, while reducing the negative impacts of agriculture on the environment and contributing valuable ecosystem services.

2. Economic and social mechanisms leading to the concentration of farms and specialization of territories

The specialization of territories is primarily related to their agronomic potential, competitive advantages and such structural factors as farm size. At the same time, the workloads involved in animal production and the increased size of farms has led to the disappearance of livestock-farming systems in areas such as the Paris basin, which now specialize in annual crops. On the other hand, the desire to maintain employment in a region can also lead to specialization. This was the initial reason for the development of the livestock-farming sector in Brittany in the early 1960s, where specialization and concentration were subsequently reinforced by economic logic. These mechanisms of territories specialization have been well studied in the case of animal (Larue et al., 2011 for pig sector in Denmark; Roe et al., 2002 for pig sector in US, Gaigné, 2004 for pig sector in France, Ben Arfa et al., 2010 for dairy sector in France).

2.1. Consequences for land use of the specialization of territories and intensification of farming systems

In Europe, the specialization of territories and intensification of farming systems has been accompanied by changes in land use. As a result of the development of cereal crops and the growing of maize silage for ruminants, there has been a sharp decrease in permanent grassland areas and the growing of pure forage legume crops. Between 1967 and 2007, the permanent grassland area in the EU-6 (France, Germany, Italy, Netherlands, Belgium, Luxembourg) decreased by 7.1 million ha (about 30% of the 1967 figure) (Eurostat, 2010a,b). The tendency was similar in France (−4 M ha, i.e. −30%), the Netherlands and Belgium. Where the EU-27 is concerned, the grassland area has decreased by 15 million ha. Even marginal grasslands tend to be abandoned, particularly in mountainous and Mediterranean areas, and many grassland areas (up to 30%) have also been abandoned in new member states (NSI, 2004, 2005). Notable exceptions are Ireland and UK, where the acreage of permanent grassland has been maintained at a high level (respectively 75 and 65% of utilized agricultural area UAA), whereas permanent grassland acreage averages just 31% for the 27 European countries. In France, the acreages of lucerne (*Medicago sativa* L.) and red clover (*Trifolium pratense*) have decreased by 75% over the last 30 years. These forage legumes accounted for 1.0 million ha in 1970 but only 321,000 ha in 2000 (Pflimlin et al., 2003), whereas over the same period the area devoted to maize silage increased from 350,000 ha to 1.4 million ha. At the same time, the acreage of peas (*Pisum sativum* L.) decreased from 700,000 ha to less than 200,000 ha (UNIP, 2011). These changes were encouraged by the CAP reform of 1992, which was favourable to cereals and very unfavourable to legumes and grassland, at least until the mid-term review for grasslands.

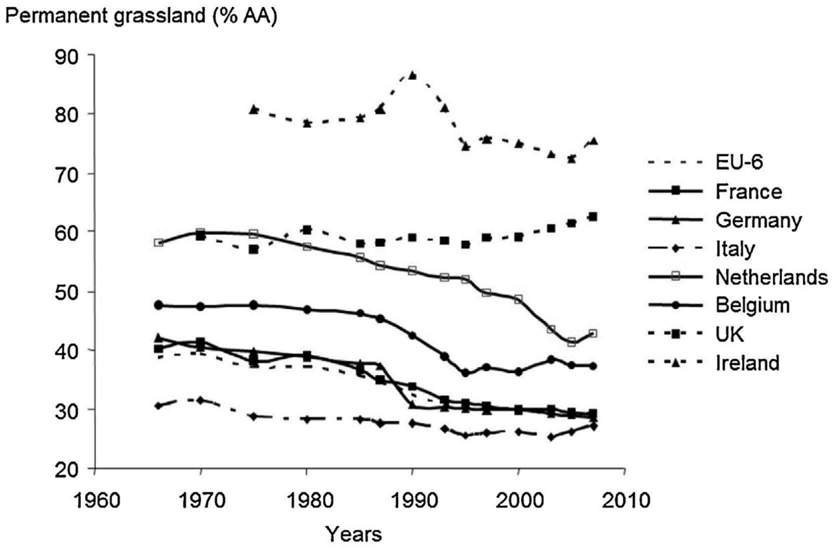
At the same time, crop rotations have been greatly simplified. Until the 1960s, a balanced rotation included between six and eight crops, thus ensuring a high degree of diversity. Empirical research indicated that this was the best solution for maintaining soil fertility, restricting the development of pathogens and limiting the use of mineral fertilizers, symbiotic N fixation being the primary source of N for crops and recycling of organic N the second (Jensen et al., 2010). Comparison of the 1994 and 2001 data shows a marked trend towards the simplification of crop rotations. There was a very marked increase in the planting of wheat (*Triticum aestivum* L.) after rapeseed (*Brassica oleracea* L.) (25% vs. 12% of land planted with wheat), and wheat after small-grain cereals (19% vs. 13%), with a parallel reduction in wheat after "other" crops. Small-grain cereals, grain and forage maize, rapeseed and sunflower (*Helianthus annus* L.) accounted for 56% of crops preceding wheat in 1994, but almost 75% in 2001 (Le Roux et al., 2008).

Grassland acreage has also decreased in South America. The temperate portion of South America has its northern boundary at latitude 30° S, which excludes most of the subtropical areas, and covers almost 60 million ha (Cabrera, 1976; Paruelo et al., 2001). This region can be subdivided into different types of ecosystem, with the Pampas Grasslands of Argentina the most important temperate cropland area of South America. Except in the Rolling Pampa and Flooding Pampa sub-regions, where the integration of agriculture and livestock farming is only occasional, because of the respective prevalence of annual crops and cattle-raising, the land surface is used for both cropping and livestock-farming, albeit in different proportions from the other Pampa sub-regions. During the 20th century, about 65% of the Pampas region of Argentina was covered by grasslands and pastures, but this proportion had decreased to 55% by the first decade of the 21st century (Viglizzo et al., 2010). According to the National Agriculture Census (INDEC, 2012), about 8 million ha of pastures were converted to cropping (mainly soybean) between 1988 and 2002. The decrease in grasslands and pastures was common to all the Pampean sub-regions, with the exception of the Semi-arid Pampa. The process of intensification was particularly dramatic in the Rolling Pampa, where the area covered by grassland and pastures decreased from 66% in the 1956–1960 period, to 43% in 1986–1990, and 30% in 2001–2005 (Fig. 1). The grazing of livestock on these pastures has shifted to subtropical areas of Argentina, and calves are now fattened with a higher proportion of grain supplements or in feed lots (Paruelo et al., 2005; Viglizzo et al., 2010). About 1.6 million head of livestock were being fattened in feed lots in March 2010 (Subsecretaría de Ganadería, 2012). The proportion of grasslands and pastures is still as high as 56–61% in the Flooding, Semi-arid Inland and Mesopotamian Pampa sub-regions, where livestock-farming still prevails, despite significant advances in crop-growing over the last decade. The proportion of grasslands and pastures approaches 50% in the Southern (47.4%) and Sub-humid (49.2%) Pampa sub-regions, suggesting integration of crop and livestock production in both areas (Paruelo et al., 2005; Viglizzo et al., 2010).

2.2. The economic logic underlying the dual process of concentration and specialization

The process of concentration and specialization is explained by a number of concurrent factors. The savings made on certain factors of production when an installation expands are greater than those that can be made from reducing purchases of inputs (energy, inorganic fertilizers). Purchases of inputs are lower in multiple cropping/livestock systems that combine plant and animal production. In particular, faster growth in the cost of labour compared with that of energy and chemical N fertilizer has led to the specialization

a) In Europe



b) In the Pampean subregions (from INDEC, 2012)

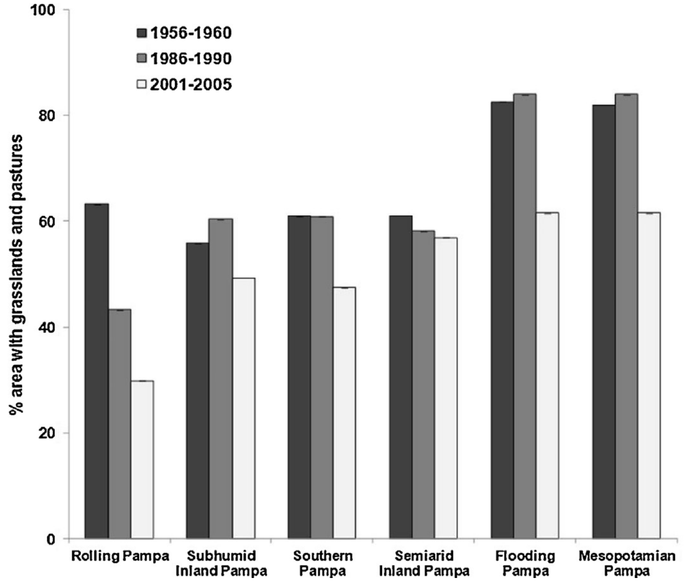


Fig. 1. Changes in areas of grassland as a percentage of total agricultural area.

and concentration of farming operations (Dupraz, 1997). Larger farms save on transaction and transportation costs (economies of scale): the more produced, the less it costs per unit (Chavas, 2008). Econometric studies show, for example, that the cost savings associated with farm size are far from negligible on European dairy farms (Tauer and Mishra, 2006) and on farms in North America (Key et al., 2008; Mosheim and Lovell, 2009). Larger farms also have more leverage in negotiating supplies of inputs. As farms specialize and grow, mineral fertilizers are used more and more in place of organic N. Over the past 20 years in France, the numbers of meat and dairy cows per herd have more than doubled and those of pig production systems have increased six-fold. Furthermore, not only has the average size of farms increased, but production has been concentrated in the largest livestock-farming systems, regardless of the type of herd. The same trends have been observed in many countries.

In temperate South America, the process of concentration and specialization may be largely explained by the introduction of no-till farming, highly specialized in the production of genetically modified soybean, and by cheaper chemical weed control with glyphosate (Paruelo et al., 2005; Viglizzo et al., 2010). The process has been driven by market demand from China, India, Japan, and other Asian countries. Soybean is used for oil and biofuel production.

At the same time, economies of scales and reductions in the costs and times of transport (Combes and Lafourcade, 2001) have encouraged regional specialization in livestock production and a growing interregional and international trade and substitute products intended for animal feeds, and soybean meal. It is worth noting that the geographical proximity of feedstuffs (wheat, barley (*Hordeum distichum* L.), maize and soybeans) is not an important factor in the location of animal production, especially in the case of pigs. This explains the huge increase in European soybean meal imports from America (Galloway et al., 2008). The geographical proximity of farmers and industries also has other benefits: it facilitates the rapid circulation of information and the development of technical, organizational and product-related innovations, as has been demonstrated in the case of pig production in France (Larue et al., 2011), Denmark (Gaigné et al., 2012) and North America (Roe et al., 2002).

In all European countries and in North America, economies of scale are also a factor favouring the spatial concentration of industries and the phenomenon of clustering, albeit in varying proportions (Bagoulla et al., 2010; Gervais et al., 2008). The geographical proximity of industries and farms results in increased efficiencies: producers are incentivized to be close to their clients to reduce the costs of transporting merchandize, to shorten delivery times, etc., and an industry can strengthen its control over suppliers. The integration of livestock-farming systems by industry also appears to favour the spatial concentration of production (Goodwin, 2005). This tendency is well illustrated by the poultry sector in France: more than 90% of farmers have signed integration contracts, and more than 60% of poultry production is concentrated in Brittany and the Pays de la Loire.

In theory, limiting manuring with waste to a maximum rate per hectare should favour the geographical dispersion of animal production but, since the costs of shipping waste to land still available for manuring are high, this has not in fact happened and land availability is not yet a limiting factor where concentration is concerned. In France, farms are authorized to treat manure in order to eliminate excess N. Public support of these technologies has in fact encouraged the spatial concentration of pig farming due to economies of scale in the volume treated: the biggest units are encouraged to treat, while the smallholdings are encouraged to reduce their livestock (Djaout et al., 2009; Gaigné et al., 2012). The Brittany region concentrates 81% of the volume of liquid manure treated, whereas it accounts for 56% of the total herd. Data from Canada (Weersink and Eveland, 2006) and the USA (Metcalfe, 2001) also show that increasingly strict environmental policies have a negative impact on smallholdings, but not the largest structures.

Strong measures have been required to (partially) counteract the trend towards increased concentration in the case of ruminant production. EC policies, for example, have addressed the geographical distribution of ruminants. In France, suckler cow premiums, as well as subsidies for the maintenance of grassland and to compensate for natural handicaps, have supported the presence of ruminants in difficult areas. The management of milk quotas has been used as an instrument to freeze the regional milk supply and to avoid concentration, but the suppression of such quotas, planned for 2015, could favour the concentration of production in regions with competitive advantages.

3. Consequences of the specialization of territories and farming systems

Several problems are caused by the excessive specialization of farms and territories, in particular environmental problems and a reduction in the resilience of such systems to economic or climatic risks.

3.1. *The case of territories specialized in intensive livestock farming*

Livestock-farming systems are major consumers and emitters of reactive N (Peyraud et al., 2012). While the growth of plants associates C and N in stable forms, their consumption by ruminants uncouples the cycles of N from C (Faverdin and Peyraud, 2010) and generates very mobile and reactive N compounds (urea, ammoniacal and nitric forms, amino-acids), which more or less quickly find their way into water, as nitrate (NO_3), and into the atmosphere, as ammonia (NH_3) and nitrous oxide (N_2O). At the same time, animals and/or their effluents produce methane (CH_4). Territories with concentrated livestock-farming systems are currently overall N importers and the N not retained by herds is discharged from farm buildings, animal waste storage areas, grazing land and fields to which inorganic fertilizers or manure have been applied. Highly concentrated areas of livestock farming in the European Union therefore create an excess of N and cause damage to the environment. At European level, there is a clear correspondence between highly concentrated areas of livestock farming and excesses of N (Velthof et al., 2009; Leip et al., 2011), viz. in Ireland, Western Brittany and Western France generally, the region comprising Belgium, the Netherlands, Denmark and Western Germany, and finally southern Germany and the Po Valley in Italy. All scientific studies concur in linking NH_3 emissions directly to animal density (Leip et al., 2011; Peyraud et al., 2012).

Brittany is the leading French region for the production of milk, swine, poultry and eggs. Accounting for 6% of the national agricultural area, Brittany is home to a very large number of animals (RGA, 2010): 20% of the country's dairy cows, 54% of sows, 56% of fattening pigs and 41% of laying hens. The region is particularly affected by excessive N. Le Gall et al. (2005) showed that N surpluses are 79 kg N/ha/year on average in Brittany compared to a mean figure of 30 kg/ha/year for France as a whole. To feed its livestock population, the region imports large quantities of cereals, soybean cake and N fertilizers. According to the Brittany Economic Council (CESB, 2011), N supplies to soil from livestock farm waste are about 206,000 t/year (2006–2008), to which we must add inputs of industrial N fertilizers amounting to about 100,000 t/year. Nitrogen flows to the oceans have been estimated at 75,000 t/year (from 20,000 to 160,000 t depending on the year), i.e. equivalent to one quarter of the amount of N ending up in the soil, causing green tides. Between 2007 and 2010, the volume of algae collected increased from 27,000 to 61,000 m^3 despite investment in manure storage and the treatment of about 10,000 t/year of pork liquid manure.

Intensive fattening with high concentration of livestock in feed lots can be expected to cause groundwater pollution in the subregions of the Pampas, although the moderate nitrate content observed in some places has been attributed to N mineralization after ploughing of grasslands on organic N-rich soils, rather than to their fertilization history (Portela et al., 2006).

Very concentrated livestock-farming systems also result in high percentages of P in soils (GIS Sol, 2011: group of interest for science), and the figures are still rising. This is alarming because of the impact of P on water quality and the eutrophication of agrosystems. These areas are very largely in excess because of inputs of P with feedstuffs and mineral mixtures. The accumulation of P in soils to which livestock-farming wastes are repeatedly applied also results in an N:P ratio (4–5) much lower than optimal value for crops (6–8) (Eghball, 2003; Sharpley and Smith, 1994). This is even more the case with composts, with N:P ratio even lower because of losses of N during composting. Apart from intensive livestock-farming areas, the GIS Sol (2011) report speaks of relatively low P contents within many French soils. This juxtaposition of situations of surplus and potential insufficiency raises the question how livestock effluents could be better used to correct the imbalances.

Specialization should not always be seen as negative for water quality, when such specialization is not accompanied by concentration. Several territories that specialize in extensive ruminant farming systems based on permanent grassland (Grand Massif Central, Jura, Alps) in fact have N surpluses lower than 15 kg N/ha/year (Bertrand et al., 2007; Le Gall et al., 2005). These territories face other problems, however. The proliferation of field voles (*Microtus arvalis*), encouraged by the presence of permanent grasslands and the absence of any mechanical intervention on the soil, generates damages which may consistently reduce forage production (Benoit et al., 2007). The reduction in forage yields averages 30 to

80%, depending on the paddock/height of the sward and the density of voles. Meadows which are only mown in spring have a high sward height and provide protection for this species, which is very prolific.

Besides creating systemic imbalances, specialization also decreases the overall resilience of farming systems and the animal food chain to specific events. It also increases economic risks. Europe is a large importer of grains and soybean cake for livestock feed, mainly from North and South America, despite the fact that the continent exports agricultural products and fertilizers (Galloway et al., 2008; Leip et al., 2011). Today, Europe imports 3 million tonnes of proteins. Moreover, these commercial exchanges tend to concentrate N inputs in the territories specialized in intensive livestock management. Where France is concerned, the protein deficit was around 40% in 2010–2011 (SNIA, 2012; UNIP, 2011), i.e. approximately 1.2 million tonnes. Imported soybean accounts for 52% of proteins consumed by livestock. In the production of pork, 2 million tonnes of peas were used in the 1990s, as compared with only 0.15–0.20 million tonnes in 2010–2011 (SNIA, 2012). The livestock sector's heavy dependence on imported proteins makes it very sensitive to price changes. A case in point is soybean-oil cake, the price of which has risen in just two years from less than €200/t to more than €550/t.

3.2. *The case of territories specialized in intensive crop production*

The disappearance of livestock and associated grassland is generally accompanied by a reduction in ecosystem services. Lemaire et al. (2003) reported that pastures can help agricultural systems to regulate environmental flows and so achieve multiple environmental benefits, which is no longer possible when cereal rotations are simplified. Grasslands are increasingly being recognized for their contribution to the preservation of soil stability and fertility, conservation of biodiversity, regulation of physical and chemical flows in ecosystems and mitigation of pollution (MEA, 2005).

Increased use of pesticides up to the 1990s (UIPP, 2004) caused water contamination and loss of biodiversity. Small-grain cereals, maize and rapeseed, which occupy approximately 35% of UAA in France, account for nearly 60% of the pesticides sold. The French Institute of Environment's annual compilation (IFEN, 2004) bears witness to the widespread contamination of surface and ground waters by pesticides, and a preponderance of herbicides amongst the most frequently detected compounds. Given the importance of securing the quality of drinking water supplies, local authorities are obliged to take concerted action, as in the case of the Communauté d'Agglomeration de Poitiers (Guérin and Barré, 2007).

Maintaining a sufficient percentage of soil organic carbon (SOC) has several benefits: improved soil structure, resistance to erosion, regulation of the N cycle, the supply of nutritive elements to plants, water-holding capacity and the promotion of active biological life (Matson et al., 1997; Ciais et al., 2010). The loss of SOC has been identified as a major threat to soil as a resource (European Commission, 2010), while small but consistent increases in SOC could mitigate the effects of climate change by storing atmospheric CO_2 (Lal et al., 2007; Soussana et al., 2010). In France, arable lands are characterized by relatively low levels of SOC (40 t/ha in the first 30 cm), permanent pastures by higher values (approximately 70 t/ha) and wetlands by much higher values (up to 300 t/ha) (Arrouays et al., 2002). National surveys conducted in Belgium (Lettens et al., 2005) and the Netherlands (Kuikman et al., 2002) have also found a higher SOC content in grassland than in arable land. The conversion of permanent pasture into arable land leads to a decrease in SOC. This is the case in Brittany, for example, as recently reported in a survey of the quality of French soils (GIS Sol, 2011). The soils of the Rolling Pampa are similarly affected by SOC decreases and structural deterioration as a result of long-term agriculture (Alvarez et al., 2009). In Argentina, SOC has decreased by 30–40% over the last 10 years in Pampas soils subjected to cultivation. OM content has stabilized in the last few years, however, as soils have been managed under no-till farming systems (Díaz-Zorita et al., 2002; Alvarez et al., 2009).

Grasslands included in crop rotations store C (0.5–1.2 t/ha, Soussana et al., 2010) and this storage increases with their duration, since the C loss associated with the conversion of pasture into arable land is twice as rapid as the storage promoted by the opposite change in land use (Arrouays et al., 2002). The effect of different rotations, both including and excluding grass, on SOC content has been intensively studied in South America. A long-term experiment conducted by INIA Estanzuela in Uruguay (Gentile et al., 2005) highlights the advantages of rotations including temporary pasture for the dynamics of organic matter in the first 20 cm of soil (Fig. 2). After 40 years, SOC decreased by 2.2–1.5% in cultivation systems involving the use of fertilizers, whereas SOC levels were maintained in the case of rotations including pasture, even if grass was grown only for a short time. The SOC dynamic is rapid each time a new pasture is established: during the pasture phase, most of the organic C lost during the arable phase is recovered (García-Prechác et al., 2004).

Soil organic C, especially the particulate fraction (POC), usually increases during the pasture period and decreases during the first 3 or 4 years when land is in the crop-production phase (Díaz-Zorita et al., 2002; García-Prechác et al., 2004; Gentile et al., 2005; Franzluebbers and Stuedemann, 2009). In the Southern Pampas, SOC and POC are expected to decrease when pasture soil is cropped. This decrease is greater under conventional tillage than under zero-tillage agriculture and is of greater magnitude in crop sequences consisting of soybean than in those consisting of maize and wheat. SOC and POC are expected to recover after three years of land being laid to grass in the Southern Pampa (Studdert et al., 1997).

The risk of soil erosion caused by ripping and the transport of particles under the action of rain and run-off is a function, amongst other things, of land use. Grasslands and adjacent structures such as hedges can slow down the run-off and favour the dispersion and infiltration of surface water, thus reducing the risk of erosion. At the European level, annual losses of soil average 0.3 t/ha under grassland and 3.6 t/ha under arable land. The enlargement of fields and associated disappearance of hedges and other landscape features, as well as farm specialization, which creates situations where a group of homogeneous and contiguous plots carry the same crop at the same stage of development at the same time, also increases the risk of soil erosion. This phenomenon can be seen in such areas as Haute Normandie (France), where the frequency of mud flows has been increasing since the early 1990s. Such areas of arable land are very sensitive: the gentle slopes, associated with soils of poor stability, create serious problems in the absence of grass cover (Papy and Douyer, 1988; Ouvry, 1992). In the Pampas region, soil erosion has been significantly reduced since the implementation of zero tillage (Díaz-Zorita et al., 2002; Alvarez et al., 2009) (Fig. 3).

The impact on biodiversity of the use to which agricultural land is put is widely recognized. The reduction of diversity and complexity of habitat on different scales associated with the simplification and specialization of the farmed landscape is a critical process leading to a loss of biodiversity on agricultural land (Benton et al., 2003; Geiger et al., 2010). By comparing 25 European landscapes (16 km^2 each) in seven countries, Billeter et al. (2008) showed that all the taxonomic groups considered (vascular plants, birds and five groups of arthropods) increased with the proportion of semi-natural elements in the landscapes. The existence and acreage of grassland within a landscape matrix, as well as the associated hedges and other non-crop habitats, helps to maintain a specific biodiversity and has a critical role in shaping the distribution and abundance of organisms of different trophic levels (Bretagnolle

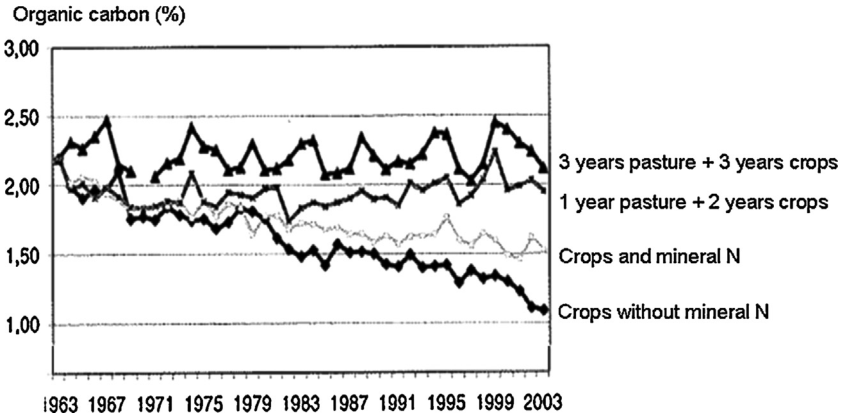


Fig. 2. Changes in soil organic carbon (SOC) content according to rotation (Diaz-Rossello et al., 2006).

et al., 2011), especially such not-very-mobile species as the organisms living in the soil. It is also well established that field edges, the extent of which decreases with the enlargement of fields, play a very positive role in increasing floral diversity and the number of crop auxiliary arthropods (Marshall et al., 2006). Agronomic practices at the field level also play a part in reducing biodiversity. In particular, the use of pesticides and other plant-health products is one of the major factors responsible for the severe decline of biodiversity in cultivated agro-ecosystems (Burn, 1988; Le Roux et al., 2008). The simplification of rotations is also regarded as one of the factors responsible for the decline of soil fauna (notably earthworms) and micro-organisms in Europe. Crop rotations are often seen as a means of avoiding the proliferation of specific pathogens in a given crop (Alabouvette et al., 2004). It has been shown that the integration of a perennial crop in a rotation increases the specific wealth and abundance of invertebrates (Pérèz et al., 2011).

With the increase in the size of farms, the rural population has generally decreased in territories specialized in cereal production. A study was conducted recently evaluating stakeholders' expectations of agriculture in mountain and in lowland territories. Animal production was overwhelmingly recognized as a driving force in social and territorial dynamism, in terms of direct or indirect employment, services, organized activities, etc. As well as the production function, which was recognized by all protagonists (local councillors, extension workers, food chain and tourism professionals) in both types of territory, the major role of animal production in maintaining rural life was very much stressed. Animal production was also seen as an aspect of heritage, and its role in the maintenance of natural environments was emphasized in both regions, mainly by researchers, consumers and ecologists.

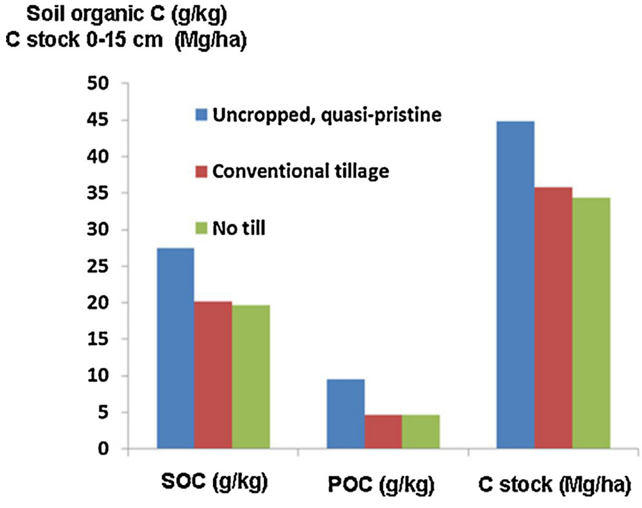


Fig. 3. Soil organic carbon (SOC), particulate organic carbon (POC) and total C stock in pampa soils (from Alvarez et al., 2009).

4. Possibilities for reconnecting livestock and crop production: prospects, limitations and the need for innovation

Mixed-farming systems can potentially achieve high levels of production, conserve natural (water, air) and non-renewable resources (phosphorus, fossil energy), attenuate the greenhouse effect, produce ecosystem services (pollination, soil fertility, pest control), and halt biodiversity loss through integration of crop and animal production and ecological engineering (Wells et al., 2000). After decades of farm and territorial specialization, the partial (re)localization of animal production in territories specialized in crop production will be difficult for organizational, social and economic reasons (see part 2), although some pioneering experiments have already taken place in Europe. Changes are also taking place in Argentina. The majority of cropland in the Pampas (nearly 20 million ha) is used for large-scale, continuous cropping, based on the extensive use of zero-till farming, extensive application of herbicides and the prevalence of soybean within the crop rotations. Although this production system is economically sound, at least in the short term, it produces few agricultural products. This has resulted in a renewed interest in reintegrating historical crop/livestock production systems and crop/pasture rotations (Díaz-Zorita et al., 2002; García-Prechác et al., 2004; Fernández et al., 2011). The expected benefits of a crop/pasture rotation system include reductions in herbicide use and energy demands, and increased inputs of organic C and N to the soil (Díaz-Zorita et al., 2002; García-Prechác et al., 2004; Gentile et al., 2005). In this section, we examine strategic approaches to developing alternative mixed-farming systems that reconnect animal and crop production at farm, district and landscape level. We consider animal localization, agronomic practices and use of animal waste.

4.1. Reintroducing livestock farming to farms or territories specialized in cereal production: a new opportunity?

In France, a few arable farms have recently reintroduced sheep herds. This movement is still marginal but these pioneering systems, and the underlying motivations, have recently been subject to examination (CIRPO, 2012). Sheep production can give a new balance to cereal farms. The ewes and lambs can make perfect use of all areas subject to environmental constraints, such as the obligation to plant catch crops, by grazing from August to December.

They also use other farm products, such as cereals, straw or lucerne, as well as a wide range of by-products which are often available in large quantity and at low cost in these territories (beet pulp, wheat distiller's grain, etc.). In return, their manure is efficiently used by the first crop in the rotation, such as maize, beets or sunflower. A herd of 200 ewes produces 710 kg of N, 770 kg of P and 1050 kg of K, sufficient to fertilize about 15 ha each year, thus reducing outlay on fertilizers. Manure also increases SOC in the long term. Diversification of this kind creates additional income and employment. The workload involved in livestock management need not be too demanding if the lambing period is planned to fall outside peak periods of agricultural work. Additionally, the production of lamb meat can counteract volatility in the price of cereals.

4.2. *Agronomic practices that use nutrients more efficiently and increase livestock protein self-sufficiency*

4.2.1. *Using pastures for recycling nutrients and regulating environmental flows in mixed-farming systems*

Grassland helps to control environmental flows within agricultural systems and provides many other environmental benefits (Lemaire et al., 2003; Peyraud et al., 2010). A comparison of optimized livestock farm systems that differ in the proportion of maize and grass in animal diets provides evidence of lower N losses in systems that rely more on pasturing. A large proportion of permanent pasture minimizes the risk of leaching associated with crop management (Peyraud et al., 2009). Many European countries, including Ireland, the Netherlands, Denmark and Germany, have considered recycling of this kind and consequently have raised the organic N supply ceiling from 170 kg N/ha/year, as set by the Nitrates Directive, to 230 or 250 kg N/ha/year for grassland areas, provided they account for a large proportion of UAA (often from 70 to 80%).

There are many ways in which this N is used and recycled: by biomass that is active over a long period, by soil that can assimilate a large proportion of the excess N in organic form, and by the absence of soil without plant cover (Decau et al., 1997; Peyraud et al., 2012). In their synthesis, Decau et al. (1997) showed that, in spite of great variability in the conditions of each experiment, urinary N is distributed on average as: 25–30% assimilated in soil, 30–35% recycled by plants, 25–30% lost by leaching, 10% lost as ammonia, and <5% lost as N_2O and N_2. Finally, ammonia emissions are lower when animals graze rather than when stall-fed (10 vs. 25%; Peyraud et al., 2012). Nitrate losses under pasture conditions are often low, except in the case of highly fertilized temporary pasture (Vertès et al., 2007, 2010) or with frequent ploughing. Losses under pasture/crop rotations reach 80 kg N ha^{-1} y^{-1}, when pasture is introduced for only three years, but are lower for longer rotations (40–60 kg ha^{-1} y^{-1}), when pasture is established for five or more years (Vertès et al., 2010). Moreover, ploughing temporary pasture in spring rather than in autumn not only reduces the risk of leaching but also tends to increase the yield of the following crop because of the preservation of residual N. Simon (1992) has shown that the corn silage yield is 15% higher on former pasture in the first year and 9% higher in the second year. Some older experiments in the USA have also shown that yields of cereals are improved when they were part of rotations comprising one or two years of forage crops, as compared with traditional corn/soybean rotations (Adams et al., 1970).

As well as providing proteins for ruminants, pastures produce other environmental benefits, limiting P run-off (Le Gall et al., 2009) and helping to mitigate the greenhouse-gas balance of the livestock sector through C sequestration in grasslands (Soussana et al., 2010). Carbon sequestration by grassland and hedges compensates for between 6 and 43% of greenhouse gas emissions, depending on the systems utilized (Dollé et al., 2011). However, a regional study of integrated crop/livestock systems on the Rolling Pampa found that SOCand POC were similar in continuous cropping systems and in integrated crop/livestock systems (Fernández et al., 2011). Grassland also contributes to an overall reduction in pesticide use. A recent European survey showed that pesticide use is inversely proportional to the grassland areas of farms (Raison et al., 2008). Le Gall et al. (2009, 2012) have summarized the environmental performance of dairy systems using different proportions of pasture and maize silage, based on a survey of 195 French dairy enterprises (Table 1). Performance was better in all systems relying more on pasture.

Table 1
Environmental performance of dairy systems according to the proportion of maize silage in the agricultural area.

% Maize	Low (10–30%)	Medium (30–50%)	High (>50%)
Number of farms	67	100	28
Maize (% AA)	22	39	62
Others crops (% AA)	34	42	37
Milk (kg/cow)	7315	7924	8136
Stocking rate (LU/ha)	1.4	1.7	2.5
N surplus (kg/ha/year)	58	93	112
P surplus (kg/ha/year)	6	5	10
Energy (ML/l milk)	2.4	2.6	2.8
Net C footprint (kg equiv. CO_2/l milk)[a]	0.84	0.92	0.98
Pesticide (*n* treatments/ha SAU)	0.77	1.27	1.28

Adapted from Le Gall et al. (2009, 2012).
[a] Including C storage under grassland.

Finally, efficient grassland management can combine environmental and economic efficiencies. Comparisons at the global level show that dairy systems maximizing the use of grassland appear to be highly competitive (Dillon et al., 2008). These authors have shown that the total cost of production is negatively related to the proportion of grass in a cow's diet, and is therefore 50–60% higher in Denmark and the Netherlands than in Ireland. Similar results have been obtained in France, showing that dairy systems using grazing are highly competitive (Peyraud et al., 2010). However, many livestock farmers see grazing management as a complicated practice and associated with an image of "holding on to the past". The (re)emergence of these innovative systems will therefore require the mobilization of all actors involved in research and development and an increased effort to provide training.

4.2.2. *Using forage and grain legumes for increasing N and energy efficiencies in mixed-farming systems*

The major advantage of legumes is their capacity to fix atmospheric N. The percentage of N in a pea plant resulting from symbiotic N fixation is approximately 70–80% and thus one can estimate that a pea crop fixes approximately 180–200 kg N ha^{-1} in the above-ground biomass (Vertès et al., 2010). The quantities of N fixed in above-ground biomass by mixed white-clover (*Trifolium repens* L.)/ryegrass swards vary from 150 to 250 kg N ha^{-1} (Vertès et al., 1995). This means that the autonomy of a pasture in terms of N nutrition is achieved as soon as white clover exceeds 25–30% of the biomass. No direct financial or fossil-energetic cost is linked to this N entry.

Studies of nitrate leaching generally show that losses are lower in mixed pastures of grasses and white clover or other legumes than in highly fertilized pure grasses (Hutchings and Kristensen, 1995; Ledgard et al., 2009). This is explained by the fact that mixed pastures do not support such high animal loads as fertilized grass pastures, and to a lesser extent by the biological regulation of N fixation by soil. Vertès et al. (1997) have found a 5 to 10% reduction of nitrate leaching under mixed clover/grass pasture, as compared with fertilized pure-grass pasture. Fewer data are available for other legumes, but – yield for yield – losses through leaching seem to be lower in the case of mixed lucerne/grass pasture than for mixed clover/grass pasture (Russelle et al., 2001). Planting lucerne for the third year in a wheat-beet rotation leads to a noteworthy reduction in nitrate leaching (Muller et al., 1993). In this trial carried out using lysimeters, the nitrate content of water was 92 and 123 mg L^{-1} on average over 10 years, in both the presence and absence of lucerne. Legumes also contribute to reducing N_2O emissions (Muller et al., 1993; Ledgard et al., 2009). In 2006, the IPCC adopted new guidelines for estimating N_2O emissions in agriculture: N from legume crops was excluded as a source of N_2O emissions in the 2006 IPCC guidelines. Legumes contribute to reducing the prevalence of diseases and improve soil fertility and are thus excellent rotation starters. It would seem that the introduction of legumes into rotations has a positive effect on microbial diversity, resulting in a reduction in the severity of diseases of telluric origin (Lupwayi et al., 1998; Kloepper et al., 1999).

Moreover, legumes produce forage and grains that are rich in proteins, thus contributing to the protein self-sufficiency of livestock-production farms. Forage legumes can sustain high animal performance. Diets based on a mixture of maize silage and red clover or lucerne silage (Chenais, 1993), lucerne hay or big bales (Rouillé et al., 2010), as compared with a pure maize-silage-based diet, led to similar dairy performance while reducing the amount of soybean meal needed to meet animal requirements. It should, however, be pointed out that conservation/storage problems (quality of silage; loss of leaves during hay-making) often affect the quality of conserved legumes and that special care must be taken in their production (Arnaud et al., 1993). In grazing systems, the beneficial effects on animal performance of white clover within white-clover/grass pastures have been amply demonstrated (Wilkins et al., 1994; Ribeiro-Filho et al., 2005). One of the most decisive advantages of white clover is that the rate of decline of nutritional quality throughout the plant-ageing process is far less than for grasses. Ribeiro-Filho et al. (2003) have shown that herbage intake declines by 2.0 kg day^{-1} on pure rye-grass pastures, as against 0.8 kg day^{-1} on mixed pastures. This makes mixed pastures easier to manage than pure grass pastures. Legume grains such as peas or faba beans (*Vicia fava)* can partially replace soybean meal in the diets of dairy cows (Brunschwig and Lamy, 2002) or fattening pigs (Gatel et al., 1989).

There appear to be some limitations where the development of legumes is concerned. The productive performance of grain legumes is a controversial topic. The productivity of legumes is low in comparison with cereals or beets, and this is a major reason why they are not more widely grown. The difference is still increasing, and at present in France, the mean yield of peas averages 4 t/ha, as against 7 t/ha for wheat (UNIP, 2011). However, it is important to take a long-term view in assessing the use of legumes, as they provide N for the following crop (Jensen and Hauggaard-Nielsen, 2003; Justes et al., 2009). For example, wheat yields are generally higher after a crop of winter peas than in a conventional rotation (Justes et al., 2009). Assessments of grain legumes, such as peas, must be carried out at the rotation level, taking into account all the ancillary effects on the following crops. Variations in the margins obtained during rotations including and excluding peas are low (either positive or negative according to price scenarios, Schneider et al., 2010). Several experimental devices have recently been designed in France (Justes et al., 2009) to assess systems that include grain legumes. Where forage production is concerned, mixed white-clover/grass pastures are generally less productive than highly fertilized grasses but recent data from projects conducted in Europe show that mixing several well-suited species (two legumes and two grasses) can overcome this obstacle (Kirwan et al., 2007). Although the introduction of lucerne into cereal rotations offers many advantages, the use of lucerne produced in a specialized non-livestock farm raises the issue of achieving complementarities between farms.

4.2.3. *Using catch crops and permanent cropping to better manage N*

The role of catch crops in reducing the risk of nitrate leaching has been known for a long time (Simon and Le Corre, 1988). Their long-term effect has been the subject of recent work, with convergent conclusions (Justes et al., 2012). This is one explanation for the regulatory inclusion of the practice of planting catch crops in sensitive catchment areas and vulnerable zones (Peyraud et al., 2012). They contribute to the reduction of winter losses of N, increase the stock of organic matter in the soil and help to limit the risk of soil erosion. NFICs are very valuable in reducing leaching between ploughing grain legumes or pastures and the following cereal crop, because cereals do not have the capacity to absorb all mineral N, and in fact they are valuable in all rotation schemes that leave the soil uncovered during the drainage period. Mustard (*Sinapis hirta*) appears to be particularly effective, absorbing up to 80 kg N ha^{-1} in only two to three months of growth (Justes et al., 2012). However, mustard is not a forage plant and, in mixed-farming systems, it is more advantageous to use a catch crop that can then be consumed by animals, such as green rapeseed, or more complex mixtures, for instance mixtures containing cereals, and clover. Their valorization by the animals improves the total productivity of the production system and does not penalize the productivity of the following cereal (Franzluebbers and Stuedemann, 2007), while providing a feed resource. The environmental value of fodder beets, because of their long growth period, can extract ~400 kg ha^{-1} of available N after pasture has been ploughed (Morvan et al., 2000). However there is currently a lack knowledge of the potential of different species, especially those that are not cultivated today, but which could be interesting in the future.

The association of cereals and protein crops established in the autumn can produce 10–11 t dry matter ha^{-1} of forage silage in June with the use of little or no N fertilizer or pesticides, while providing soil cover during winter (Naudin et al., 2010). However, the nutritive value of the forage produced is relatively modest (Emile et al., 2011), therefore the feed should be reserved for heifers or distributed in limited quantities to dairy cows. Advancing the harvest date by one month improves the forage quality but greatly reduces yield (by about 40%). A suitable compromise therefore has to be found. In addition, results vary with the cereals used, wheat giving substantially reduced yields, as compared with beardless triticale. We still lack knowledge of the potential of different species or groups of species that can be used to enhance the uptake of available soil N by crops, while producing high-quality forage and reducing the risk of the development of pathogens.

There is growing interest in permanent cropping systems that keep soil covered. These are beginning to be studied in France (Carof, 2006), but more research is required before they can become operational. The growing of cereals over a permanent cover of legumes that provide both N and protection against leaching has so far proved difficult to bring under control. Similarly, attempts to sow cereals on grazing pasture without destroying the pasture (by ploughing or chemically) have thus far proved inconclusive: the herbage cover enjoys a competitive advantage, not allowing satisfactory development of the cereal.

4.3. *Efficient recycling of animal waste to reduce mineral N utilization*

Manuring with liquid livestock manure rather than inorganic fertilizers results in similar crop yields and does not cause additional losses on a timescale of about 15 years (Leterme and Morvan, 2010), provided that supplies/inputs are carefully geared to plant needs (fractionated applications in the spring) and that manuring is avoided in the autumn, before the drainage period.

In the case of liquid manure, N losses occur primarily as ammonia (NH_3) emissions. These losses occur in buildings, during storage and during the spreading of livestock residues. They range from 20 to 75% of N excreted (Gac et al., 2007). Reducing NH_3 emissions increases the quantity of N that can be made available to plants and recycled. It is possible to reduce emissions in buildings by carefully adjusting the N content of diets to animal requirements. An unbalanced N supply leads to increased urinary N excretion, which is highly volatile (Hayes et al., 2004). Depending on diet, the amount of NH_3 emissions can vary from a ratio of 1–5 (from 40 to 200 g per cow day^{-1}) in dairy cows, with no difference in milk yields (Aguerre et al., 2010). Increasing the frequency of manure evacuation also reduces NH_3 emissions from 20 to 60% (Peyraud et al., 2012). NH_3 emissions during storage can be reduced by covering the pit or putting a floating cover on the pit, which leads to the formation of a crust, or by reducing the surface area of the storage pit per unit volume. NH_3 emissions can be further reduced by 25–35% by using localized application techniques, and by up to 70–90% if liquid manures are buried by injection or ploughing immediately after spreading (UNECE, 2007; Peyraud et al., 2012).

Manure treatments may also be an effective way of reducing emissions (Peyraud et al., 2012). The acidification of liquid manure shifts the NH_3–NH_4^+ equilibrium towards NH_4^+ and thus limits the potential for volatilization. Phase separation provides two products that can be managed differently (and potentially better): a solid phase with total N and P concentrations 2 and 4–5 times higher than those of the starting product, and a liquid phase (less than 2% dry matter) with N primarily in the form of ammonium (85%), rapidly available for crops (Béline et al., 2003). There is also the possibility of exporting the solid phase as fertilizer to other agricultural regions. Composting involves the controlled decomposition of animal waste to eliminate easily biodegradable organic matter and to transform residual organic matter into stable molecules similar to those characteristic of moist organic matter (humus). However composting solid manure leads to substantial but highly variable N losses, depending on the extent of process control. Such losses have been estimated at between 30 and 60% of input N, primarily in the form of NH_3, which represents up to 90% of losses (Bernal et al., 2009).

Prediction of N fertilizer value is generally based on classifying by "type of product". N bioavailability in the year following application is low for solid manure and composted wastes (20–40%), high for liquid phases and poultry droppings (70–100%), and intermediate for liquid manure from pigs and dairy cows (30–50%, Peyraud et al., 2012). Recent research on the dynamics of NH_3 emissions after manure spreading (Morvan et al., 2006) has given us a better understanding of variations in N efficiency. This has resulted in several measurement tools that can be used for characterizing the N bio-availability of manure (e.g. Quantofix), and software applications for adjusting fertilization (e.g. Azofert, Machet et al., 2007). Nonetheless, it still remains difficult to adjust the mineral N supply with any precision after manure spreading as, in taking decisions, farmers are faced with variations in the organic-matter composition of manure. Further progress needs to be made in our knowledge of the N mineralization dynamics of effluents, particularly in interaction with different soil types, and the mineralization of native soil N.

As well as providing N fertilization, supplying organic matter in the form of animal waste (manure or compost) increases SOC, but the process is very variable. C storage resulting from the addition of cattle manure varies from 10 to 30% in the case of liquid manure and 20–60% in the case of solid manure. Increases in SOC content have proven to be variable, depending on the experimental site (Morvan et al., 2010; Peltre et al., 2012). Animal wastes have also a positive effect on the microbial diversity of soil, because they are a source of various nutrients for native micro-flora and a complex inoculum (Bittman et al., 2005; Lalande et al., 2000).

4.4. On what geographical scale should we be considering new mixed-farming systems?

The partial re-localization of production systems between territories with the goal of reducing the negative impacts of regional specialization and the intensification of farming systems is not possible, because of organizational and economic constraints in the agri-foodstuffs sector. The current model, characterized by territorial concentration and regionalization of the livestock sector, does not realistically allow for radically different developments. There are also social reasons: given the workload, livestock operations rarely return to territories where it has been abandoned. Hence, the transfer of nutrients between farms and/or territories is a more promising approach to improving nutrient management and reducing the need for inorganic fertilizers.

4.4.1. Transfers of nutrients between neighbouring farms

Specialized animal farms (especially pig farms) often do not have sufficient land surface to manage their liquid manure. The aerobic digestion of pork liquid manure leads to the elimination of about 60–70% of N content in the form of N_2 (Béline et al., 2003, 2004). This technique is effective in reducing the total N load, but does not preserve the N resource, as 40% of the herd's N intake is lost, and this will become very costly in the future. Alternatively, specialized farms can transfer manure to other farms or territories. There have been a few studies of collective manuring plans, involving the transfer of wastes from exporting farms (pigs, poultry) to receiving farms (herbivorous, crops). Lopez-Ridaura et al. (2009) have studied the advantages of developing collective plans of this kind. Using the life-cycle analysis method (LCA), they compared two procedures for managing N surpluses: aerobic treatment and transfer. The results indicate that, for all environmental indicators considered (eutrophication, acidification, climate change, energy consumption) impacts of transfer between farms are two times less than impacts of aerobic treatment. These results concur with those obtained at the individual farm level. Baudon et al. (2005) concluded that the recycling of elements, particularly N, is always the best solution from an environmental point of view. However, the collective organization of such transfers requires a good combination of equipment, crop rotation, soil type and climatic conditions (Paillat et al., 2009). These practices also raise questions of their social acceptability to local residents.

Looking from the other end, it is conceivable that crop farms producing lucerne to diversify their rotations might redistribute the feed to livestock farms. Examples have been described in the United States where groups of crop farmers produce fodder grain and forage for their neighbours and, in return, receive effluent to fertilize their fields (Franzluebbers et al., 2011). Transfers of this kind between farms make it possible to combine the economic and environmental benefits of each system. In particular, annual-crop producers can benefit from a greater diversity of crops in their rotations and better management of the C and N cycles. Increases in crop yields at farm level have also been reported (Franzluebbers, 2007). However, it is difficult to know at present whether such interactions between farms can result in the same productive synergies as when mixed farming is practiced at the individual farm level. The social conditions for the success of such collaborative ventures will also need to be clarified.

4.4.2. Several geographical scales can be considered

Another question is to determine on what geographic scale this recycling is to be done and how it is to be implemented. Complementarity between specialized livestock farming systems (mainly pigs) and cereal farms may also be considered on a broader geographical scale, but this requires the development of technologies to reduce the volumes of waste that would have to be transported over long distances. Deodorizing and sanitizing of these effluents are also important issues to consider.

In the case of solid manure, composting results in a final product rich in essential plant nutrients (N, P and K) compared with the initial solid manure, and with no foul odours, which is an asset for its transport. Drying slurries in order to produce normalized fertilizers is a promising idea. The aim is to produce standardized and marketable organic fertilizers so that these products (N and almost all P) can be more easily exported to other regions, especially regions where large-scale farming is practised, where they could at least partially replace inorganic fertilizers. A preliminary step is the separation of phases, as the solid phase contains much higher concentrations of total N and P (two and four-to-five times higher) than the starting product. Pioneer groups of pork producers/pig farmers already collect and recycle the slurries of their members by integrating drying into their industrial organization, using the heat available at a particular stage (slaughterhouse or methanization), and export the fertilizers. Exchanges between territories would offer the possibility of better P management at national level. However, the competitive advantages or drawbacks of these treatment systems, as compared with those of inorganic fertilizer production, have still to be determined: economic efficiency, LCA assessment and social acceptance have not yet been documented.

5. Conclusions

Specialization of farms and territories associated with intensification of production systems has for many years been a mainstream trend in Europe and in South America. These systems were developed in an era of low-cost energy, but their future is questionable from an economic and environmental point of view. Mixed-farming systems have many advantages in achieving high land productivity and ensuring good incomes for farming enterprises, while at the same time conserving natural resources and producing valuable ecosystem services. They can also make an important contribution to increasing the resilience of the agricultural sector against climatic and economic constraints. Closer integration of arable and livestock farming, and the development of legume cropping, can reduce the dependence of the agricultural sector on external inputs (mineral fertilizers, protein feeds, pesticides) and careful recycling within agro-ecosystems can minimize nutrient losses. The closing of nutrient cycles can be envisaged on various scales, from an individual farm or small agricultural region to the regional or national level. These possibilities need to be explored from an economic, technical and social point of view. To achieve the desired objective, these mixed systems will need to be combined with innovative agronomic and livestock-management practices, and new organizational practices. Agricultural policies and public action are important factors in encouraging a transition to these new forms of organization.

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