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Une école d'ingénieurs au cœur de la vie

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Une école d'ingénieurs au cœur de la vie

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1 Introduction

The ongoing rapid growth in world population imposes a continual pressure to produce sufficient food. Compared to today, additional two billion people are forecasted to reach a world population of up to 9.1 billion in 2050 (United Nations 2009). Crop yields are actually rather falling than increasing, notably in many of the warmer and poorer regions of the world as a result of rising temperatures and increasing natural disasters, and these are regions where population growth is high (Ray et al. 2013). Currently, yields of the world's four most important crops (maize, rice, wheat, and soybean) are only increasing about 0.9-1.6 % at a time when global agricultural production would need to increase by around 60-110 % by 2050 in order to keep up with mid-range population growth estimates. Tilman et al. (2011) estimate that crop demand may increase by 100-110 % between 2005 and 2050. Nevertheless, these scenarios disregard allocation and storage problems, overproduction, and food waste in some world regions.

Besides the medical advances, global food production during the green revolution increased fast enough to support the world's rapidly growing population. Nevertheless the impact of the Green Revolution in terms of producing sufficient food was quite different in the different continents of the world. In Europe or North America for example, we have for many years witnessed an "overproduction" with high quantities of food produced for export to other continents. To a certain degree this was facilitated by subsidies for agricultural production and export, which also made it possible to outcompete agricultural production in certain developing and emerging countries.

Although the Green Revolution provided a significant increase in food production, the intensification of food production has also led to negative externalities such as biodiversity loss (Millennium Ecosystem Assessment

Photo A. Wezel

2005), human health issues (e.g. food contamination with pesticides, health problems of farmers due to pesticide application), and eutrophication of lakes, rivers, and sea areas, observed, for instance, along the Brittany coasts, France (Ménesguen and Piriou 1995, European Communities 2002). Although the water quality of lakes and rivers in Europe generally improved over the last 20 years, mainly due to the installation of sewage treatment plants, the degradation of water quality in many drinking water catchments remains a significant problem, mainly due to diffuse pollution with nitrates and pesticides from agriculture (European Environment Agency 2003, Lerner and Harris 2009, European Commission 2011). The world-wide model of the Green Revolution reaches also other limits with increasing energy and fertiliser prices, the ever increasing use of pesticides (Drogui and Lafrance 2012), and insufficient outreach to smallholders.

Therefore, there has been an increasing demand over the last decades to not only maximise production but to also satisfy the increasingly diverse expectations of society. Agricultural production issues have recently been expanded to include ecosystem services other than food or fibre provision (Zhang et al., 2007). Like natural and semi-natural ecosystems, agroecosystems can provide ecosystem services such as carbon sequestration, pollination, or water filtration. It will be necessary to improve food production and resilience for all types of agriculture, be it conventional, integrated, or organic and whether on a small or large scale.

For many years, there has been a highly divergent, on-going debate around the most appropriate agricultural production practices that are simultaneously environmentally friendly, socially fair and economically beneficial (e.g. Huang et al. 2002, Tilman et al. 2002, McNeely and Scherr 2003, Prasifka et al. 2009, Doré et al. 2011, Ervin et al. 2011, Médiène et al. 2011, Kremen et al. 2012, Lidder and Sonnino 2012, Malézieux 2012, Mannion and Morse 2012). Agricultural options range from high technology-

Photo A. Wezel

based practices to ecological-based practices. On the one hand, precision farming (Srinivasan 2006, Mondal and Tewari 2007) or use of genetically modified crops (e.g. Huang et al. 2002, Ervin et al. 2011, Lidder and Sonnino 2012, Mannion and Morse 2012) could help match the future food demand. On the other, practices based on better use of biological regulation mechanisms at different levels such as natural biological control of pests at field level, and integrating natural landscape elements into agricultural landscapes in order to decrease pesticide use (e.g. Altieri and Nicholls 2004, Gurr et al. 2004) are possible options. Other practices such as no or reduced tillage that increase soil biota activity and improve soil fertility (Holland 2004) can also contribute.

These latter options are among so-called agroecological practices, practices which are based on ecological processes and provision of ecosystem services. Agroecological practices contribute to the different goals of sustainable agriculture: to provide sufficient food for a growing world population, while not being a detriment or risk to the environment, to limit use of non-renewable energy, and to ensure economic viability for farmers.

2 European agricultural policies and agroecological practices

Agricultural and environmental policies have strong influence, and frame the modification or the implementation of sustainable practices. In Europe, the combination of policies such as the Common Agricultural Policy (CAP), European Directives (e.g. Nitrate or Water Framework Directives), European nature conservation policies such as NATURA 2000, and national policies have supported changes in the agricultural sector. Therefore, these policy frameworks and regulations have to be taken into account if modifications of agricultural practices are intended at national or European scale.

Reforming the Common Agricultural Policy: a longstanding issue

The most important policy is the Common Agricultural Policy (CAP) which has profoundly shaped European agriculture since it was set up in 1962. Its original goals were to expand and regulate the production of commodities (mainly cereals, sugar, meat, and milk products) in order to attain European food sovereignty, and to support farmers' livelihoods through guaranteed prices and strongly organised commodity markets. The CAP was first reformed in 1992, to be competitive with world market prices and to reduce its costly expenditures. Doing so, direct aids per hectare have been introduced to compensate for the decline in farm gate prices, and accompanying measures have been proposed to take care of the environment, landscape and natural resources.

The CAP still remains a crucial policy framework in organising the EU farming and agrifood sectors. Thanks to large expenditures, e.g. market and direct aids in Pillar 1 and rural development measures in Pillar 2, EU farmers continue to be supported. Those public support features have progressively moved from a focus on commodities within a highly protected regional domestic market towards a world market-oriented paradigm where farmers are mostly supported through premium instead of prices. Even as the highly-subsidised EU agriculture has become a contentious issue within multilateral trade talks, decoupled direct payments and non-trade concerns such as multi-functionality, food safety standards and environmental public goods have reinforced the backbone of the reformed CAP.

However, the environmental footprint of the EU farming sector remains high. The intensification of European agriculture, in part guided by the CAP, has often been achieved at the expense of significant environmental damage. Although the reforms undertaken since 1992 have made room for more environmental aspects, the programs in place to develop more agroecological approaches still remain inadequate or insufficiently attractive to farmers. Farming practices can have a significant impact on soil, water, and biodiversity in Europe. Whether through the system of guaranteed prices or direct subsidies, the CAP has fostered specialised and intensified production systems which dominate on the richest soils while more extensive systems are mainly found on poorer soil or less-favoured areas where climate and soil limit production. As a result, we have observed (Bureau 2007):

- A decline in permanent pasture surfaces,
- A shortening in crop rotations, with fewer species under cultivation,
- An increasing proportion of cereals both in European crop rotations and animal feed,
- A high dependency on external inputs such as chemical fertilisers and pesticides in production systems,
- A concentration of commodities production around processing sites.

Photo A. Wezel

As a direct result of the subsidies granted under the CAP, European agriculture has evolved in the direction of maximised productivity combined with high dependency on external inputs such as fertilisers, pesticides, and energy. Even decoupled, the remaining direct payments are linked to historic reference prices that are increasingly distant from current practices. In addition, the way in which public support of research and development has been directed, combined with the modus operandi of farmers and the food industry, has not significantly contributed to slowing down unsustainable patterns. The strengthening of CAP Pillar 2 measures in favour of certain forms of agriculture remains an opportunity, also to take into greater account the environmental aspects, but the overall budget is still dominated by Pillar 1 direct subsidies.

While at the beginning of the previous decade an EU communication on sustainable agriculture had been a reference for future CAP reforms (European Commission 1999), there is at present no clear EU strategy in support of agroecology and sustainable agriculture. Up to now, national action plans and political will towards a large set of agroecological practices remain marginal. Among the 28 Member States, some countries may have set up different agri-environment measures, but France is alone in having set up an explicit national agroecological strategy (i.e. "Agroecological project for France" in December 2012; Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt 2013).

3 Agroecological practices

Several well-known agricultural practices have been widely used for a long time in agriculture such as organic crop fertilisation, diversified crop rotations, or biological pest control. However, during the last two decades, these practices have been increasingly described as "agroecological practices" (e.g. Altieri 1995, Arrignon 1987).

The term "agroecological practices" emerged in the 1980s within the development of agroecology (Wezel et al. 2009). Today, agroecology as a practice is one of three major currents or interpretations of agroecology, the others being a scientific discipline and a movement. Examples of agroecological practices mentioned in literature are as diverse as cover crops, green manure, intercropping, agroforestry, biological control, resource and biodiversity conservation practices, or livestock integration (Altieri 1995, 2002, Arrignon 1987, Gliessman 1997, Uphoff 2002, Wojtkowski 2006). A recent review evaluated different cropping practices, and what the specific characteristics are that identify them as agroecological practices (Wezel et al. 2014). The present publication will focus on agroecological practices of agricultural systems under temperate climates (Table 1). We will also include agroecological practices from mixed crop-livestock systems, and in particular, we will provide concrete examples of the different practices currently applied in France and in Europe.

Agroecological practices can be characterised as agricultural practices aiming to produce significant amounts of food, which seek to valorise ecological processes and ecosystem services by integrating them as fundamental elements in the development of the said practices, as opposed to simply relying on external inputs such as chemical fertiliser and synthetic pesticide application, or on technological solutions such as genetically modified organisms (Wezel et al. 2014). This assumes that biological processes are able to replace chemical or physical inputs, or to interact favourably with them, and to limit external costs, in particular environmental costs. Agroecological practices contribute to improving the sustainability of agroecosystems while being based on various processes such as nutrient cycling, biological N-fixation, natural regulation of pests and diseases, soil and water conservation, biodiversity conservation, and carbon sequestration. Some of these practices have already been applied in varying degrees in different parts of the world for years or decades, while others were more recently developed and still have a limited rate of application.

Table 1 groups the different agroecological practices into two major categories: 1) E and S (Efficiency increase, Substitution) practices, and 2) R and D (Redesign and Diversification) practices. Efficiency increase refers to practices that reduce input consumption (e.g. water, pesticides, and fertilisers) and improve crop productivity. Substitution practices refer to the substitution of an input or a practice (e.g. replacing chemical pesticides by natural pesticides). Finally, Redesign refers to the change of the whole cropping, or even farming system, and Diversification refers to practices which integrate a higher diversity of cultivars, crops, or production systems.

Table 1. Different agricultural practice categories and their respective agroecological practices.
E=efficiency increase, S=substitution, R=redesign, D=diversification. Note that one practice could correspond to one or more categories of the ESRD framework.

Agricultural practice category	E,S,R,D	Agroecological practice
Efficiency increase and substitution practices		
Cultivar and crop choice	E,S	Use of site-adapted cultivars and crops
	E,D	Cultivar mixing
Crop fertilisation management	E	Split fertilisation
	S	Biofertiliser
	E,S,R	Organic fertilisation
Weed, pest and disease management	S	Natural pesticides
	S	Biological pest control
Water management	E	Drip irrigation
	R,D	Soil erosion control with integration of landscape elements
Redesign and diversification: practices of cropping systems		
Tillage management	E,S,R	Direct seeding into living cover crops or mulch
	E,S,R	Reduced tillage
Soil covering	S,R,D	Cover crops
Crop rotations	S,R,D	Diversified crop rotations
Crop associations	E,S,R,D	Intercropping
	E,S,R,D	Relay intercropping
Weed, pest and disease management	S,R,D	Allelopathic plants
	S,R,D	Push and pull systems
Redesign and diversification: integration of production systems		
Agroforestry	E,S,R,D	Integration of timber, fruit or nut trees on cropped fields
Mixed crop-livestock systems integration at farm or landscape level	S,R,D	Substitution of non-locally produced cereals and soybean in mixed crop-livestock systems
	S,R,D	Integration of natural and semi-natural rangelands into mixed crop-livestock systems
Management of landscape elements at field, farm, or landscape scale	S,R,D	Integration of semi-natural landscape elements for biological control
	S,R,D	Integration of semi-natural landscape elements for pollination
	R,D	Integration of semi-natural landscape elements for erosion control

Many agroecological practices include, to different degrees, a diversification of systems (Figure 1). This ranges from integrating more diversity at the field and farm levels (e.g. cultivar, crop association, cropping system, production system level), or even to integrating biodiversity in the surrounding area (semi-natural landscape elements). An overview is provided in Figure 1, which also distinguishes the scale of application. The question of diversification will be more extensively dealt with during the presentation of the respective agroecological practices and chosen examples.

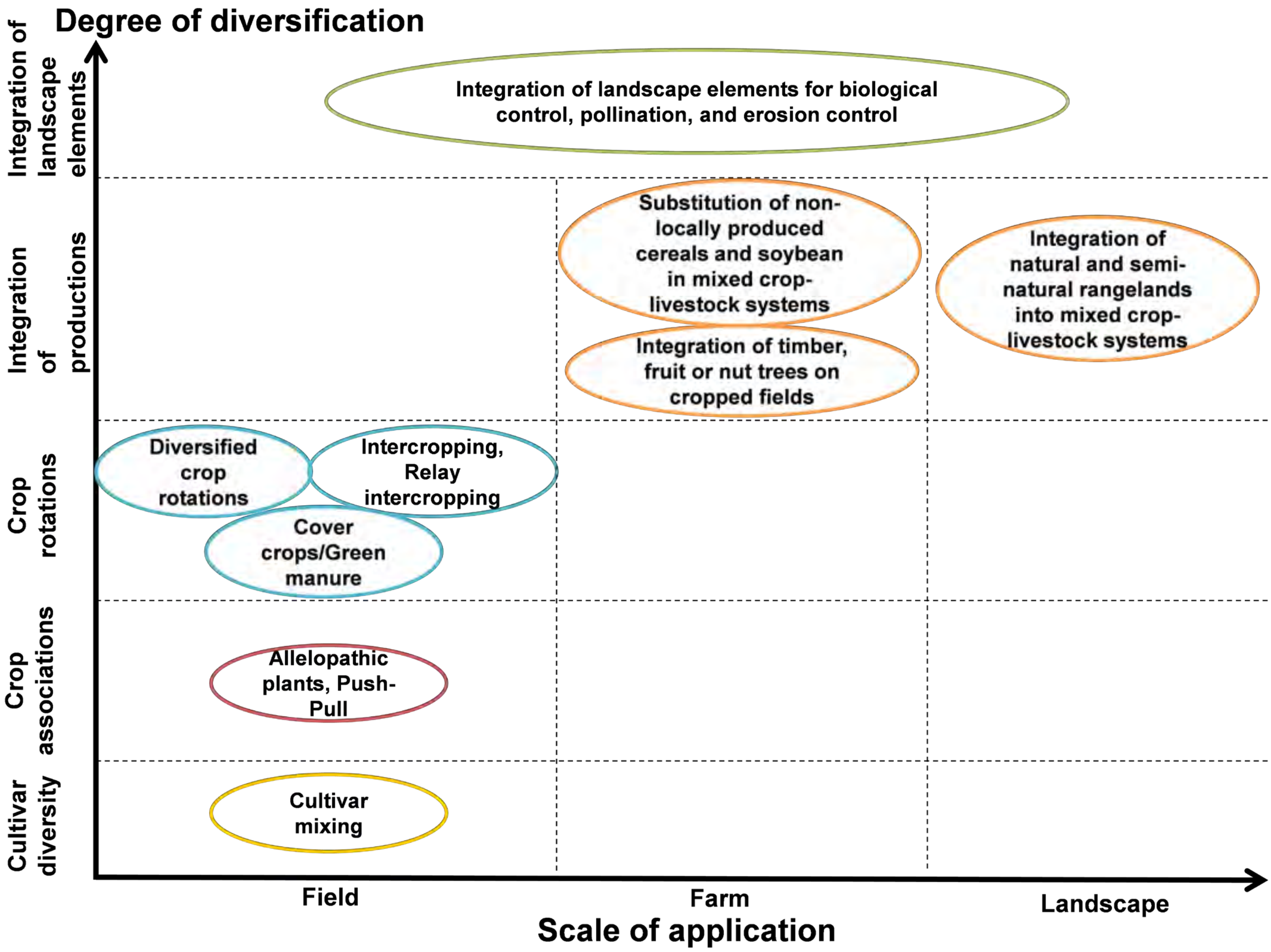

Figure 1. Agroecological practices which integrate a higher diversity of cultivars, crops, production systems, and landscape elements. Practices are placed along a diversification gradient from intra-species diversity via crop and production systems diversity to integration of landscape elements.

3.1 Efficiency increase and substitution practices

Efficiency increase practices aim to reduce inputs such as water, pesticides, and synthetic fertilisers, while maintaining or improving crop productivity. Substitution practices rely on the substitution of an input or a practice, e.g. replacing chemical pesticides by natural pesticides, or implementing biological control. In the following, different agroecological practices which increase efficiency or substitute inputs will be presented and illustrated with examples.

3.1.1 Use of site-adapted cultivars and crops, and cultivar mixing

In modern crop production, each plant is often almost genetically identical to its neighbours, allowing insect pests and pathogens to easily move from plant to plant and decimate crop yields if there is no chemical protection. Increasing plant diversity in agricultural fields may reduce pest abundance and damage, and reduce pesticide use (Tooker and Frank 2012). Basic and applied research is increasingly demonstrating the value of intraspecific genetic diversity for improving ecosystem stability and function. Thus, a more practical way of diversifying crop fields may be to increase plant genotypic diversity by planting cultivar mixtures or crop mixtures. Choosing an adequate crop and cultivar can help to improve crop resistance to abiotic stresses (N and water deficiency), pathogens, and diseases (Tilman et al. 2002). Combining crop resistance to spatial or temporal crop diversity (rotation and spatial allocation) is therefore a good opportunity for reducing pathogen resistance, and coping with climate variability and decreasing dependence on synthetic inputs (Döring and Wolfe 2009).

Another important point is to choose crop species or cultivars which favour the development of beneficial soil microorganisms stimulating plant growth by way of different mechanisms, i.e. enhanced nutrient acquisition, protection against pathogens and modulation of phytohormone synthesis, such as arbuscular mycorrhizal fungi (AMF) or plant growth promoting rhizobacteria (PGPR). AMF constitute a key functional group that favours crop growth and agroecosystem sustainability. Soil characteristics, soil management and plants influence their development and effectiveness for plant productivity (Gianinazzi et al. 2010). The diversification of crop rotations and the reduction of non-mycorrhizal crops (e.g. rapeseed) could enhance arbuscular mycorrhizal fungi populations and diversity. Various authors (Desclaux et al. 2008, Gianinazzi et al. 2010) also highlight the importance of changing breeding strategies from a selection of plants adapted to high fertilisers and pesticide use to a selection of plants maximizing the adaptive capacity of plants. For instance, this should be done by introducing other criteria like weed competition, nutrient use efficiency, and plants adapted to AMF attributes under low-input environments. Plant growth promoting rhizobacteria (PGPR) constitute another key functional group that favours crop development by increasing the supply or availability of nutrients to the host plant, or by helping to control pathogenic organisms (Malusá et al. 2012, Vessey 2003). Numerous cropping practices influence the density and effectiveness of PGPR, for example, tillage, organic amendments, or liming. Crop species and cultivar also influence these microbial communities (Hartman et al. 2009).

In spite of scientific evidence, mixing cultivars or choosing crop species or cultivars which favour the development of beneficial soil microorganisms that might contribute to improved pest control and yield have not been widely adopted owing to logistical and financial constraints. For instance, marketing cultivar mixtures may be severely limited in the cereal sector. Marketing procedures and processing quality are often cited as major limitations to the use of mixtures.

Examples from France

New societal values call for the diversification of agriculture by the consumer to be a source of specific quality linked to local conditions, by the farmer to have adapted genotypes to specific environments, and by the citizen to address the biodiversity issue. Participatory plant breeding programs have appeared in European countries to promote biodiversity and sustainable agriculture and provide fitting responses to the diversity of environmental conditions and end-users needs. The contribution of farmers to the creation and maintenance of genetic diversity is beginning to receive more recognition in developed countries. For instance, organic farmers have become involved in the conservation and use of landraces and historic varieties because these varieties possess agronomic and quality traits that have been not found in modern varieties (Dawson et al. 2013). Participatory plant breeding programs conducted in Europe have concluded that the genetic diversity conserved on farm is complementary to gene banks indicating that both systems are required for more efficient cultivar and crop diversity conservation.

In another approach, long-term selection programs at INRA, France, aim to create new winter bread wheat genotypes adapted to low-input and organic agriculture through a professional, dedicated selection process (Figure 2). After 20 years of selection and screening under two different crop management systems, low input and organic, Hendrix and Skerzzo, two pure lines, were registered in 2011 in the official catalogue with the special mention "organic farming". For the second year of seed production, 150 ha were sown in autumn 2013 to be sold to organic farmers in 2014. This successful process was made possible by the support of the agricultural organic sector, which was associated in the initiative along with all the stakeholders involved in the ITAB (Institut Technique de l'Agriculture Biologique) network. A second step is currently underway to select varieties specifically bred for organic conditions. INRA's breeders are thus pursuing their research to create new varieties with all the components producers have demanded, in particular a strong ability to cover the soil to suppress weeds more efficiently.

Figure 2. Winter wheat breeding program at INRA (National Research Institute for Agronomy, France). This program started in 2000 for the selection of existing materials and the creation of new genotypes for low-input and organic agriculture (Photo B. Rolland).

3.1.2 Spilt fertilisation, biofertiliser, and organic fertilisation management practices

Fertilisation management helps to balance the supply of nutrient and crop demand in time and quantity. Long-term studies have consistently shown the benefit of manures, adequate fertilisation, and crop rotation in maintaining agronomic productivity by increasing C and N inputs into the soil. However, the lack of synchronization of crop nitrogen requirements and availability of soil nitrogen from organic matter and materials, such as crop residues, green manures and composts, is known to affect yield and quality. The use of synthetic fertilisers help achieve optimum production, though improper applications can cause environmental damage on air, water, and soil quality.

The application of organic manures causes enhanced soil biological activity (Birkhofer et al. 2008, Steenwerth et al. 2008) and potentially increases soil mineralisation. Nevertheless, the application on a field may include higher labour and energy demands, and difficulty in optimising N-availability in soils with organic fertilisation as well as in meeting plant-demand (Sanchez et al. 2004). Moreover, obtaining off-farm organic fertilisers might be difficult, expensive and may even incur undesirable transport costs (e.g. manure) for stockless systems. Nutrient management on stockless farms is generally considered as more critical than on animal farms because these farms cannot rely on nutrient imports through feedstuffs. Phosphorus and potassium budgets are particularly hard to balance since there is no atmospheric input (such as N fixation) for these nutrients (Berry et al. 2003, Nowak et al. 2013). However, the farming system does not entirely account for nutrient management. Importing fertilizing materials may not only be determined by the chosen farming system but may also be determined by the regional context such as having neighbouring livestock farms with an excess of manures.

An effective means of improving nutrient use efficiency in agricultural crop production is splitting fertiliser application. The objective is to match the supply of nutrient to the crop demand in time (Fageria and Baligar 2005, Zebarth et al. 2009). This improved matching of supply and demand also helps to limit ground and surface water contamination by fertilisers. However, it requires increased labour, and estimating crop N demand might be difficult. Precision farming, using sensor and GPS technologies, could improve the application of fertilisers by varying rates and mixtures as needed with reference to inter and intra-field variability in crops.

Utilization of biofertilisers is another way to reduce fertiliser inputs and improve nutrient availability. Biofertilisers are substances with free-living microorganisms that are applied to seed, plant surfaces, or soils. These microorganisms colonize the rhizosphere or the interior of the plant, and thus increase the supply or availability of nutrients to the host plant (Vessey 2003). Three major groups of microorganisms are considered biofertilisers: AMF (arbuscular mycorrhizal fungi), PGPR (plant growth promoting rhizobacteria), and nitrogen fixing rhizobia (Malusá et al. 2012). Increased yields, and uptake of N and some other elements through PGPR inoculation (Singh et al. 2011) or AMF inoculation (Pellegrino et al. 2011, Ortas 2012) have been reported. Therefore substances with free-living bacteria applied to seed may benefit crops by stimulating plant growth or by reducing the damage from soil-borne plant pathogens. But this technology still needs further improvement and a better understanding of the different conditions and features of the interrelationships in the soil-plant-microorganism system in the field (Malusá et al. 2012). Moreover, studies showed quite high variability and inconsistency of results between laboratory, greenhouse, and field studies.

Sustainable fertilisation management in France and Europe

Sustainable fertilisation management is based on the combination of chemical and organic sources supporting plant growth and maintaining soil fertility while minimizing losses. It is essential to adapt crop rotations to nutrient supply, to consider soil fertility and their in-field heterogeneity, and then to optimize crop nutrition for yield and quality. Advances in scientific understanding of soil and plant behaviour led to the design of soil-crop models supporting decision support systems. Precision technologies are used for gathering information about spatial and temporal differences within the field in order to match inputs to site-specific field conditions. For instance, Diacono et al. (2013) illustrate advances in precision nitrogen management of wheat using technologies gathering information about spatial and temporal differences within the field in order to match inputs to site-specific field conditions. In recent years, there has been growing interest in sensor-based application of N rates and time. Several authors in Diacono et al. (2013) showed that nitrogen use efficiency was considerably greater and grain yield variability was lower for the sensor-based fertiliser recommendation than for common farmer practice.

Advances in the prediction of N availability of organic sources such as organic fertilisers, manures and crop residues could improve nitrogen management under organic or low-input agriculture (Chambers et al. 2006). For instance, David et al. (2005) present the value of a decision support tool for managing organic N fertilisation by evaluating the economic benefits of a top-dress N fertiliser and selecting optimal fertilisation strategies according to farmers' strategies and conditions.

One of the oldest uses of microorganisms in agriculture is the inoculation of legume crops with nitrogen fixing bacteria like *Rhizobium* for example. This inoculation enhanced the nodulation of the legume crops and the quantity of N fixed. PGPR and AMF could also be used for seed inoculation in order to increase plant development. Commercialization of PGPR and AMF inoculants remains low, except for the utilization of an Azospirillum inoculant, which is available for a variety of crops in Europe and Africa (Vessey 2003).

The utilisation of PGPR is not very developed in France. Only a few examples exist such as the utilization of *Azospirillum*. In contrast, Mycorrhiza inoculations of vines, fruit trees and some tree species in plantations are more common. Mycorrhiza inoculants are now available on the market for different crop production, especially for vegetables. They are usually applied during the sowing stage. But the results on the quality and yield of the vegetables are variable. The most famous utilisation of Mycorrhiza inoculants is the one performed for the cultivation of truffles with inoculation taking place during the planting of Oak trees.

The French market of biostimulating products has been increasing for the last few years. Numerous start-ups and different companies (grouped together in the European Biostimulants Industry consortium) have developed numerous products composed of algae, plants, rock extracts and microorganisms. These products are considered as fertilisers but their utilisation is not yet clearly defined in Europe (a regulation project is expected by 2015 in Europe). Their effects on plant growth in fields are not clear and a lot of unanswered questions remain.

Box 1. Biochar

Combinations of different nutrient sources have been recently tested to limit the use of mineral fertiliser. For instance, biochar is currently a subject of active research because it can constitute a viable option for sustainable agriculture due to its potential as a long-term sink for carbon in soils and its benefits for crops.

Alburquerque et al. (2013) show that biochar addition to a nutrient-poor, slightly acidic loamy sandy soil had little effect on wheat yield in the absence of mineral fertilisation. However, addition of biochar with 100 kg N ha-1 of mineral fertilizer led to about 20–30 % increase in grain yield compared with the use of the mineral fertilizer alone. In this experiment, biochars acted as a source of available P, which led to beneficial effects on crop production.

3.1.3 Natural pesticides and biological pest control

Different agroecological practices are available to decrease weeds, pests and diseases: biological pest control, use of natural pesticides and bio-pesticides, as well as the use of allelopathic plants and push and pull systems (see 3.2.5). In general, natural pesticides and biological pest control reduce the risk of water pollution and risks to human health (e.g. Gurr and Wratten 2000, Altieri and Nicholls 2004). They might, however, be difficult to apply as their efficiency and availability depend on the pest, and they may involve increased management and costs, and require technical knowledge.

Biological pest control is based on the substitution of chemical pesticides by releasing natural enemies of pests, i.e. predators, parasitoids or pathogens, into the agroecosystems, or by increasing the populations of naturally-occurring natural enemies. Using pheromones to disturb sexual reproduction of targeted insect pests is another biological control option.

Recent initiatives by pesticide regulatory departments of European and North American governments have significantly renewed interest in biopesticide technologies as alternatives for pest management because of plans to deregister many chemical pesticides within the next 10 years (Hynes and Boyetchko, 2006). Natural pesticides, often also called botanical pesticides, botanicals, or biopesticides, have a high potential as an alternative to synthetic pesticides without the associated negative effects of the latter. Nevertheless, little is still known about them, particularly regarding larger scale applications in agriculture. Today, only a few natural pesticides are commercially used due to constraints such as variable efficiency of pest control, availability, national regulations and registration, and costs (Isman 2008). Included among botanical pesticides are, for example, pesticides which are i) derived from the seeds of trees, ii) based on plant essential oils, iii) based on pyrethrum extracted from flowers, iv) derived from crude aqueous extracts of plants, and v) based on extracts of trees (Mordue and Nisbet 2000 Coulibaly et al. 2002, Charleston et al. 2005, Isman 2006, 2008, Sinzogan et al. 2006, Batish et al. 2008, Regnault-Roger and Philogène 2008). Although these botanical pesticides are rather marginal compared to other biocontrol methods, they will be of particular interest for the growing organic sector where synthetic pesticides are not allowed, as well as for traditional agriculture in developing countries, as many of theses pesticides are derived from tropical or subtropical plants that grow naturally in such countries (Isman 2006, 2008; Regnault-Roger and Philogène 2008).

Biopesticides includes the application of bacteria, AMF inoculants or other fungi that can control deleterious organisms (Whipps 2001, Vessey 2003). These types of pesticides impact pests by antibiosis, competition, induction of plant resistance mechanisms, inactivation of pathogen germination, and/or degradation of the toxicity of the pathogens (Whipps 2001). Nevertheless, field application often fails to counteract pathogen development due to insufficient rhizo- and/or endosphere colonization (Compant et al. 2010; Verbruggen et al. 2013).

Natural pesticides and biological pest control in France and Europe

Some commercial products have been developed in the last decade such as fungi, PGPR or viruses. For example, the fungus, *Beauveria* is applied as bio-insecticide against different pests, e.g. against bugs in strawberry fields, *Leptinotarsa decemlineata* in potato fields (Todorova and Weill 2006), European corn borers in different cropping systems or different *Aleyrodoidea* larvae in vegetable production. Other fungi are also used against *Aleyrodoidea* like *Verticilium lecani* or *Paecilomyces fumosoroseus*. The

PGPR *Pseudomonas flurorescens* is spread as a natural herbicide against grass species such as *Avena fatua* or Setaria. This bacterium inhibits seeds germination and slows down the root growth of weeds. *Pseudomonas chlorophalis,* another PGPR bacterium, is used as a seed treatment for wheat, rye, or triticale as a bio-fungicide (used against *Tilletia caries*, *Tilletia foetida*, *Fusarium*, and *Septoria*).

In France, the bacterium *Bacillus thuringiensis* (well known as Bt) is commonly sprayed in vegetable and cereal cropping systems against different insects like *Pieris brassicae*, *Leptinotarsa decemlineata*, or in maize fields against the European corn borer *Ostrinia nubilalis*. Bt is nontoxic to other organisms such as mammals, birds, fishes and other beneficial insects (Iowa State University, Department of Entomology 2013).

Other biopesticides are commonly used in the world like the bio-insecticides composed of pyrethrum, rotenone or nicotine extracted from plants. The pyrethrum is the most famous and most widely-sold in the world. But they can have detrimental effects on non-target organisms.

Today, many examples exist where natural enemies are released into agroecosystems for biological control. In most cases this release of animals is conducted in greenhouses as management is more effective and the pest can be better targeted. But, increasingly, these natural enemies are also released into open fields or orchards. These natural enemies are mainly different species of ladybirds, parasitic wasps, and bugs. One example is *Trichogramma*, minute parasitic wasps, which play a key role in controlling the European corn borer (*Ostrinia nubilalis*). Different *Trichogramma* species are produced today commercially by enterprises around the world. In France, there are used on more than 100,000 ha (Naïbo and Druesne 2008). Another example is the microhymenoptera *Pseudaphycus flavidulus*, which is able to parasitise the obscure mealybug, and which was released with success in apple-producing regions in south-eastern and south-western France (Syham and Kreiter 2009).

Many farmers have also developed their own biocontrol strategies to increase the number of natural enemies and release them into their farmland. Figure 3 shows the example of a farmer who leaves infested aphid plants at the end of certain horticulture productions to attract and increase the population of natural enemies. These will then be collected or captured, and released in other production areas.

Box 2. Biopesticides market

The worldwide market of biopesticides is estimated at 2.8 billion $ at the user level. This follows unprecedented growth of 27 % per year between 2007 and 2012 (Quinlan 2013). Some economists expect the increase of biopesticide sales to continue strongly to 2020 with the greatest growth in Latin America. The European and North American markets are estimated at 830 million $ and 762 million $ respectively, and each is anticipated to exceed 1 billion $ by 2017 (Quinlan 2013). However the evaluation of this market remains difficult because it results from the sales of different commercial products which include products with plants metabolites or microorganisms, and natural enemies.

Figure 3. Pupae of hoverflies in the middle of an aphid colony on chard in horticulture systems in south-eastern France. Farmers leave certain chard plants infested with aphids even after harvest time to “produce” natural enemies. These natural enemies will then be collected or captured, and released in other plastic greenhouses (Photos A. Wezel).

Box 3. Biocontrol market

Biocontrol exists since the 1960's but took off only more recently because of increased awareness on issues linked to the intensive use of chemical products such as human health, pollution of soil and water resources, and pest and disease resistances. Today, it is supported by different international and national policies. Biocontrol products are currently used in conventional as well as organic agriculture. Today's world biological product market represents 1.7 billion €, i.e. 2% of the plant protection product market (Goulette 2013), and is expected to strongly increase over the coming years (Figure 4). The large majority of chemical companies recently intensified their activities in this sector. In France 26 companies share the biocontrol market with more than half having a turnover of less than 2 million € per year (Figure 5).

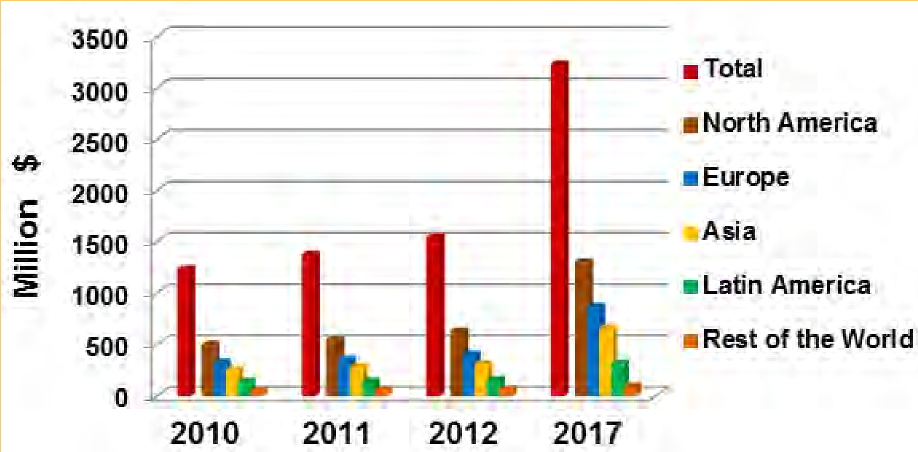

Figure 4. Growth of biocontrol market by world area. A strong increase is expected in the next years (adapted from Veronelli 2012, data from FAO, USDA, EPA).

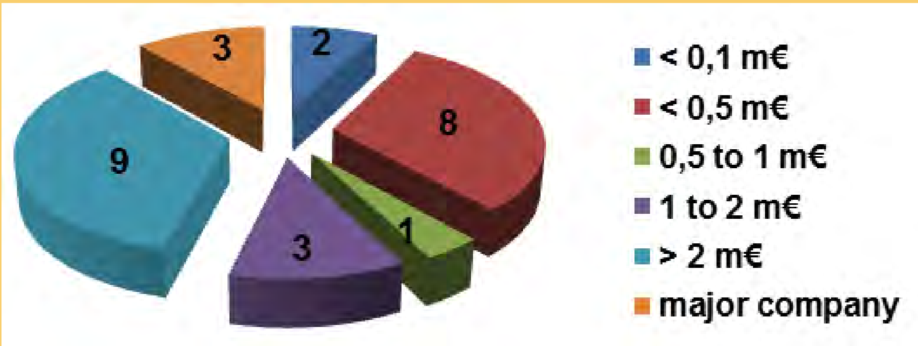

Figure 5. Number of biocontrol companies in France, and their turnover in biocontrol and biostimulation in 2012. m€=million Euros; major companies are multinational enterprises with a turnover much higher than 2 m€ (adapted from IBMA France 2013).

Mating Disruption Technique

Many species of insects use volatile sex pheromones to locate their sexual partners so that mating can take place. Female moths emit sex pheromones and males follow the pheromone trail. The mating disruption technology is based on the diffusion of large amounts of synthetically produced female pheromones, about 10,000 times more than those naturally released by females (Witzgall et al. 2010) to confuse the males and prevent them from locating the calling females.

The mating disruption method appeared in the early 1990's and has since then been used successfully in orchards and vineyards to fight against Lepidoptera pests. The number of registrations of mating disruption pheromone products has strongly increased within the last ten years (Figure 6). In France today about 50% of apple orchards are treated with mating disruption and about 22,000 ha of vineyards representing 2.7 % of the national vineyard area (Herth 2011). However the cost, either for dispensers or pheromone supplies, remains a major drawback to the adoption of mating disruption control with a very poorly competitive market and significant discrepancies in prices among countries. Therefore, in Europe, subsidy based policies can play an important role in mating disruption adoption rate: in Germany, where some Federal States provide 150 € per ha to support mating disruption adoption, 80,000 ha of vineyards, equivalent to 80% of the national vineyard area, are treated with these products (Herth 2011).

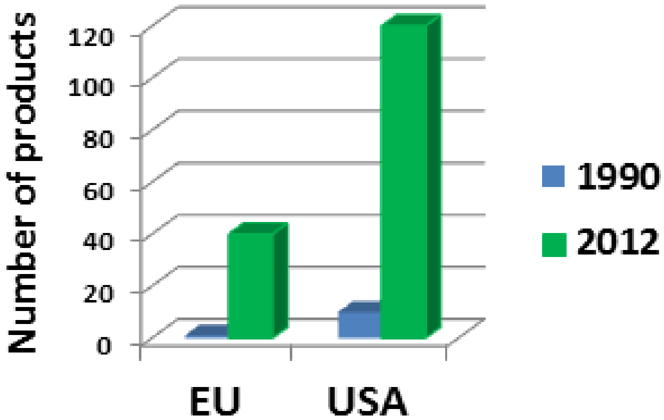

Figure 6. Number of mating disruption pheromone products registered (adapted from Veronelli 2012).

3.1.4 Drip irrigation

Water management in cropping systems is an important issue, in particular in light of the expected impacts of climate change. Moves toward greater water use efficiency, including precision agriculture, intensified use of monitoring to determine water needs, and strategic use of less than full irrigation demands are different approaches to improve water use efficiency. Here, we only deal with drip irrigation as an agroecological practice for improved water management. Although drip irrigation is not a practice which valorises ecological processes and ecosystem services, we also consider it to be an agroecological practice as it enormously reduces the external input of water which is of great importance in the context of climate change.

Drip irrigation, especially in horticultural systems, offers a high potential to limit water inputs, improve water use efficiency, and better meet the crop water demand in time and space. It also limits the risk of soil salinization. The major drawbacks are the high investment and management costs. A combination of drip irrigation and cover crops is also possible by adding cover crop rows between crops to reduce evaporation from bare soil, decrease soil erosion, increase soil organic matter, and increase N concentration if legumes are used (Lopes et al. 2011). Cover crops could also play the role of mulch.

Figure 7. Drip irrigation in nectarine orchards, southern France. Drip irrigation use is considered very important during dry and hot summer months to secure fruit production quantity as well as the maturing of certain fruit species (Photo A. Wezel).

Figure 8. Drip irrigation in horticulture systems in southern France. Vegetable production is irrigated more and more by drip irrigation systems to replace sprinklers due to increasingly scarce water resources during summer months (Photo A. Wezel).

Drip irrigation in France and Europe

Drip irrigation is increasingly used, in particular in southern France, where summers are dry and hot with low rainfall. In most cases this form of irrigation is used in fruit production (Figure 7), and to a lesser degree in horticulture (Figure 8). In certain regions in France, e.g. Provence-Alpes-Côte d'Azur, drip irrigation is used by about 20 % of farmers using irrigation to produce fruits (Agreste 2008a).

Since the 1990s more and more vine growers have also established this system in different parts of the world (Institut Français de la Vigne et du Vin 2013). Nevertheless, irrigation (including drip irrigation) in France is only allowed in certain regions and only during certain periods of the year because of wine quality issues.

A large market exists for drip irrigation systems and many enterprises offer many different types of equipment, and some even install the equipment directly on the field. In the last few years, drip irrigation has also increasingly been proposed for cereal production systems.

3.2 Redesign and diversification: practices of cropping systems

The implementation of some practices needs a redesign of the cropping or even the whole farming system because some practices cannot simply undergo slight modifications or be adapted to certain conditions. More and more practices also take into account a diversification of the system, be it intra-species diversity of crops or breeds, crop and production systems diversity, or integration of landscape elements into the agricultural systems. In most cases the diversification of systems implies a redesign of the system. This section provides examples of practices which include a diversification and resign of cropping systems. In section 3.3 examples showing diversification and redesigning of production systems will be presented.

3.2.1 Direct seeding into living cover crops or mulch and reduced tillage

The advantages of reduced tillage or no tillage (direct seeding) are reductions in energy consumption, soil erosion and soil compaction, and increases in soil biota activity and the amount of soil organic matter. No tillage corresponds to tillage practices with minimized soil disturbance (Figure 9), such as direct seeding into a living crop or mulch (Figure 10). Specific machinery may be used, such as direct seeders, which are comprised of coulter discs or tines for cutting and opening furrows for seeding. In contrast to ploughing, reduced tillage is characterised by minimal soil disturbance without soil inversion (Figure 9). The soil is only worked to a depth of 5 to 15 cm before seeding. The main goal is to reduce soil disturbance and preserve organic matter (fresh crop residues) at the soil surface or in the first few centimetres of the soil. These practices improve soil fertility to a great extent in the case of no tillage, and to a lesser extent with reduced tillage (El Titi et al. 2003, Holland 2004).

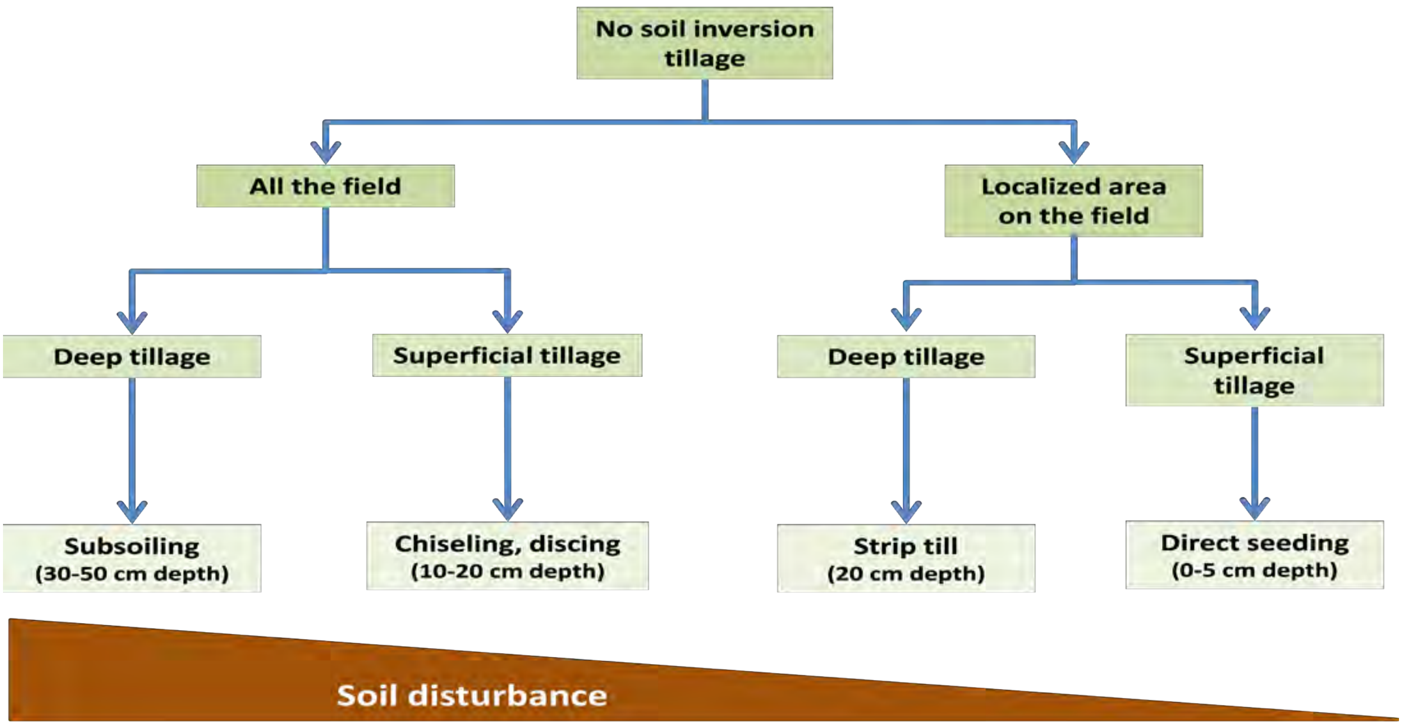

Figure 9. Different tillage systems without soil inversion: from subsoiling to no tillage. The different tillage systems are currently applied to different soil covers or to bare soil. The combination of direct sowing into a living mulch min mizes soil disturbance.

Figure 10. Direct sowing of soybean into rye in south-eastern France. This practice allows permanent soil cover and thus weed control, decreases nutrient leaching, and wind and water erosion. Also soil organic matter is increased and higher soil biota activity achieved which leads to improved soil fertility (Photo J. Peigné).

The increase in soil organic matter with reduced or no tillage practices favours soil biodiversity and promotes biological activity (Ball et al. 1998, Vian et al. 2009). For instance, with no tillage more anecic earthworms were found (Capowiez et al. 2009, Peigné et al. 2009, Pelosi et al. 2009) which increased soil porosity and thus improved water and root penetration into the soil. The impact of reduced tillage may also be found on earthworm abundance, but to a lesser extent than under no tillage management (Peigné et al. 2009). Moreover, a better control of certain pests can be expected due to increased numbers of predators, such as ground beetles (Figure 11), found in no tillage conditions (Kromp 1999).

Figure 11. Most ground beetles are important natural predators of pests. Depending on the species, their prey can vary considerably from insect larvae or pupae, (e.g. aphids, different beetles, and Lepidoptera), to earthworms, slugs, or snails (Photo A. Wezel).

A major constraint for no tillage and reduced tillage is weed control. In conventional agriculture, reduced tillage can also mean increased use of chemical fertilisers and pesticides to control weeds and maintain yields (Teasdale et al. 2007). For no tillage systems with direct seeding into mulch, the increase of herbicides is due to destroying the cover crop. In organic farming, reduced tillage often results in increasing the machine traffic for weed control, and thus increasing labour time and energy costs (Peigné et al. 2007). In temperate climates, soil compaction can occur due to climatic and soil conditions, such as in the northern part of Europe (Soane et al. 2012). All these constraints make it very difficult to draw any clear conclusion regarding the effect of no tillage or reduced tillage on crop yields. According to Soane et al. (2012), in Europe it seems that the yields of winter crops with no tillage or reduced tillage are comparable to conventional tillage with ploughing, whereas the yields can decrease for spring crops.

Tillage management and direct seeding in France and Europe

Reduced or no tillage practices are currently spreading throughout the world, including temperate areas (Holland 2004, Peigné et al. 2007, Soane et al. 2012). In Europe, around 28 million ha are cultivated using reduced tillage, and 2.35 million ha using no tillage in 2007 (Basch, 2009). So far, only 1% of the world's cultivated surfaces under no-tillage are located in Europe (Derpsch and Friedrich 2009). However, since the last decade the areas cultivated with these techniques have increased rapidly. In France, the total cultivated area no longer ploughed increased from 21 % in 2001 to 34% in 2006 (Agreste 2008b). This increase mainly concerns winter crops (Table 2). Globally, reduced or no tillage is more used with diversified crop rotations on larger farms (more than 400 ha) to reduce labour time (Agreste 2008b). Nevertheless, the main constraint mentioned for increased adoption of reduced or no tillage in France seems to be related to herbicide use (Agreste 2008b).

As compared to ploughing, farmers have noted the need to perform, on average, 0.3 additional herbicide applications on the main crops to effectively manage weeds.

To counterbalance the increase of herbicide, innovative systems have been developed from strip till to direct seeding into living cover crops (Figure 9). A key issue for farmers is the combined introduction of no tillage practices, cover cropping with diversified crops, and longer crop rotations (Thomas 2009). With diversified cover crops these farmers mainly aim at reducing the use of herbicides, mineral fertilisers (by N fixing leguminous species), and water (by reducing soil transpiration). They have also introduced others agroecological practices such as inter- or relay cropping.

A particular technique recently applied is strip tillage. It uses a tine tool which allows the soil to be worked to 20 cm depth, but just in the small area of the seeded line (Figure 12). Thus, it is a mix between no tillage (a large part of the field which remains under cover crops) and reduced tillage in the area of the seeded line. This technique, developed in the US and recently applied in France, is well adapted to row crops such as maize.

Table 2. Percentage of area with reduced or no tillage in relation to total surface of respective crops in 2000/01 and 2005/06 in France (source: Agreste 2008b).

	% of cultivated area with reduced or no tillage	
	2001	2006
Durum wheat	58	58
Oilseed Rape	35	47
Wheat	25	44
Barley	17	28
Sunflower	19	25
Grain maize	14	20
Forage maize	8	12
Sugar beet	7	15
Pea	9	13

Figure 12. Use of strip tillage in France. Only the areas of the seed lines are laboured to a depth of 20 cm. The other parts of the field remain under a cover crop with no tillage (Photo courtesy of Arvalis Institut du Vegetal, France).

3.2.2 Cover crops

A widely applied agroecological practice is the use of cover crops to limit fertiliser inputs, favour the build-up of C and reduce risk of soil erosion and nitrate leaching while enhancing retention and availability of both water and nutrients (Sanchez et al. 2004, Scholberg et al. 2010). Integration of cover crops into the rotation automatically incurs crop diversification. Soil biological activity is also enhanced and soil structure is improved (Blanco-Canqui et al. 2011), and, when legumes are used, there is provision of N supply for the next crop due to their ability to fix atmospheric nitrogen (Birkhofer et al. 2008, Steenwerth et al. 2008, Fustec et al. 2010). Cover crops can also release large amounts of labile carbon compounds promoting microbial growth and improving soil structure (Shepherd et al. 2002). However, cover crop practice constraints include a higher labour demand and potential risk of pest development (e.g. snails under cover crops), although certain species can also decrease pest pressure. For example, Brassica crops can function as cover and trap crops, but also as biocontrol, biofumigant and biocidal agents against certain insects and pathogens (Ahuja et al. 2010).

Cover crops in France and Europe

In Europe, cover crops are traditionally established before spring crops, when soils erosion often remain uncovered, to protect against soil and control nitrate leaching. Cover crops such as crucifers, phacelia, or winter rye are sown after main crop harvest. Today, farmers are not giving high priority to cover crops due to additional costs for seeds and field operations, and the supplementary time needed. New and innovative use of cover crops providing ecosystem services should be considered to encourage the use of cover crops.

Early establishment of cover crops by undersowing the main crop or by preharvest broadcasting of seeds later in the growing season would generally be beneficial as it prolongs the time of growth, guarantees growth of cover crops after harvest, and increases ecosystem services. Preharvest establishment of cover crops into a standing crop has been tested in different crop rotations, soil and climate conditions. This technique is apparently more robust and less affected by potential water saturation in Northern Europe or water stress in Southern Europe.

Undersowing systems could also affect the yield performance and quality of the main crop. For instance, Amosse et al. (2013a,b) demonstrated that undersown clover into organic wheat improved N budget of the crop rotation, and could affect the protein content of wheat and the grain yield of the succeeding maize. In Northern Europe, Thomsen and Hansen (2013) have tested the use of cover crops in different situations, by altering key factors such as sowing date, sowing technique and succeeding main crops (winter cereals or spring barley). These authors concluded that potential biomass production and nitrogen uptake were greatest with pre-harvest establishment of cruciferous cover crops rather than ryegrass. Maximum N uptake in winter cover crops established before harvest is roughly the double of N uptake for post-harvest winter cover crops. Nevertheless, germination and growth of the cruciferous cover crops have shown more variability than ryegrass. The potential for cover crop growth is therefore very dependent on the general growth conditions. For instance, water stress observed in Southern Europe may drastically affect growth in autumn. Moreover, soil temperature and humidity, time of incorporation of crop residues, and C/N ratio of cover crops all influence decomposition and breakpoint for N immobilization and mineralization.

3.2.3 Diversified crop rotations

Designing crop rotation systems aims to optimally allocate resources (e.g. land, time, energy, fertilisers, water) to improve profitability, productivity, and ecological services (Dogliotti et al. 2003, Dury et al. 2011). the benefits of annual and forage crops should both be evaluated, for the short-term impacts on yield and quality performance, and the long-term perspective on soil fertility and ecological services. Crop rotation is a traditional way of introducing crop diversity into an agroecosystem.

A major objective in diversified crop rotations is to maintain or improve soil fertility, optimise nutrient availability, and limit the need for external fertiliser. For example, the integration of leguminous plants into the rotation allows atmospheric nitrogen to be fixed, and provides an important source of N for subsequent crops. Furthermore, the crop rotation should aim at improving carbon content and soil fertility which permits an increase in soil structural stability (Dogliotti et al. 2004, Watson et al. 2002). Here, the root systems of the subsequent crop can play an important role as their roots (as crop residues) stimulate soil biological activity and improve soil structural stability. A second objective is to favour soil protection and conservation by increasing soil cover via for example the introduction of cover crops between winter and spring crops or favouring winter crops. In particular cover crops can mitigate nitrate leaching and improve nutrient availability. A third important objective of diversified crop rotations is to reduce pest and disease prevalence by avoiding the presence of successive host crops for diseases (Colbach et al. 1997a,b) and to reduce weed infestation. The latter is possible due to the specific ability of some crops to rapidly cover the soil, thus competing with weeds for soil and light resources.

The insertion of temporary grassland (<6 years) in crop rotations generates numerous services for crop production. In organic cereal systems it is often performed at the beginning of the rotation. The main forage species sown in temporary grasslands are lucerne, clover, or a combination of grass and leguminous species. These species generally provide an important development of root systems and aboveground biomass, enrich the system in organic matter (Amman et al. 2007), improve physical properties of soil such as structure, water infiltration and retention, and favour soil microbial activity (Millard and Singh 2010). Forage legumes also enrich the system in nitrogen due to atmospheric nitrogen fixation (Fustec et al. 2010). This additional nitrogen is then partly available to consecutive crops after decomposition of legume residues. Temporary grasslands are also efficient in protecting soil from erosion and sealing. Finally, temporary grasslands contribute to mitigating pests and disease development by interrupting their biological cycle. Moreover, they also compete with weeds for space and resources and are therefore an efficient means of weed control.

Diversified crop rotations in France and Europe

Crop rotations can be highly variable from one region to another. This depends mainly on soil and climate conditions, and the respective crop choice, but also on prevailing farming systems, e.g. specialised productions, mixed-crop livestock systems, and organic vs. conventional farming.

Grain crop rotation systems in France

The most frequent crop rotations carried out by grain producers in north-eastern and western France are i) 4 year crop rotation of rapeseed – winter wheat (2 years) – winter barley, and ii) 4 years sunflower – winter wheat – rapeseed – winter wheat. On these sequences, the principal pest and diseases are weeds with specific flora in spring or winter crops, insects on rapeseed (weevils and *Meligethes aeneus*) and wheat (aphids), and foliar diseases on cereals (septoria, brown rust).

To overcome problems related to the short rotations described above, different strategies to improve crop performance, and control pests and diseases were proposed to diversify crop rotation. The following principles were established as guidelines:

- Lengthen crop rotations to insert spring crops in winter crop rotation or other crops with high competitiveness to limit the producton of weed seeds. The repetition of false-sowing techniques in periods of preferential weed germination may also limit seed production.
- Introducing natural enemy species at the scale of the territory and attraction of *Meligethes aeneus* by "flower traps" at the field level to limit damage by insects.
- Adapt sowing dates, choice of resistant varieties and mixtures of tolerant varieties to manage foliar disease.

The implementation of these principles led to alternative crop rotations:

- Crop rotation 1 (8 years): Alfalfa or clover (2 years) – Winter wheat – Sunflower – Triticale – Rapeseed – Winter wheat – Spring Barley (in southern France)
- Crop rotation 2 (9 years): Alfalfa or clover (2 years) – Winter Wheat - Triticale – Winter Pea - Winter Wheat - Rapeseed – Winter Wheat – Spring Barley (in northern France)
- Crop rotation 3 (3 years): Rapeseed-Winter wheat-Spring barley

Table 3 shows the difference between the reference crop rotation and alternatives. The frequency of pesticide application per crop is most reduced with crop rotations 1 and 2. Gross margin is best with crop rotation 3, but workload is also highest. Highest N balance is found for crop rotation 0.

Conventional and organic crop rotations in south-eastern France

The second example illustrates crop rotations observed under conventional and organic agriculture in south-eastern France. There exist significant differences between conventional and organic rotation, and also if irrigation is used.

Generally, crop rotations under non-irrigated conventional agriculture are characterised by short-term rotations of cereals, oilseed crops, and spring crops (Figure 13) (Agreste 2010, 2013).

In situations with irrigation, the system is mostly based on maize monoculture (Agreste 2012) as maize is considered as the most profitable crop under the given climate and soil conditions. This monoculture system may causes weed problems (e.g. *Sorghum halepense*), pests (e.g. corn rootworm), and soil degradation (soil sealing) impairing crop performances. To mitigate these phenomena, the monoculture is interrupted every 3 to 6 years with 1 year of winter cereal. This monoculture, however, could generate a large dependency on inputs for irrigation, fertilisers and pesticides, and may cause impacts on the environment, e.g. nitrogen and pesticide leaching, and soil degradation.

Table 3. Different parameters affected by different crop rotations in France. Data extracted from INRA (2009)

	Crop rotation 0 (reference)	Crop rotation 1	Crop rotation 2	Crop rotation 3
Frequency of pesticide application per crop	5.9	1.6	1.6	2.4
Gross margin (€ per ha)	403	405	383	415
Workload (hours)	3.4	3.2	2.7	3.5
N Balance (kg/N)	36	14	19	29

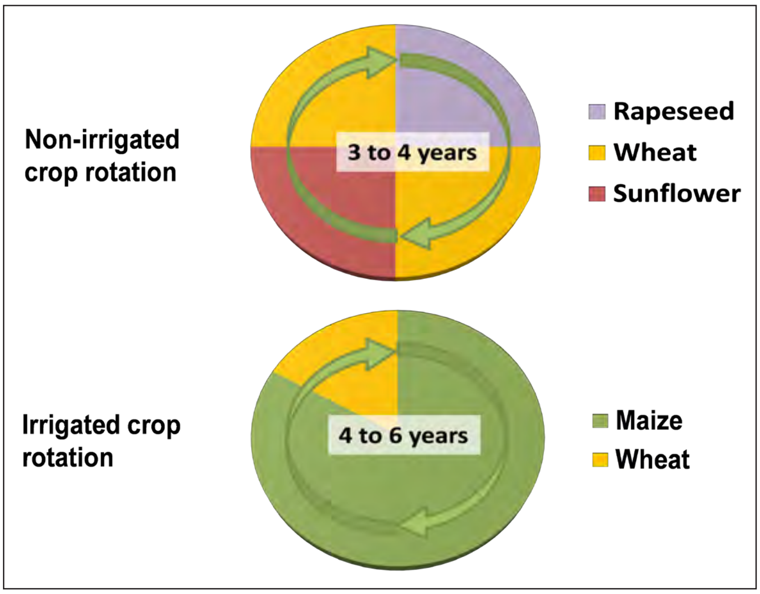

Figure 13. Typical crop rotations observed in conventional cereal farms in south-eastern France. With access to irrigation the spring crop maize dominates the rotation. Without irrigation crop rotations are shorter but more diversified.

Until recently, most organic farms included both crops and livestock production in their crop rotations. From the beginning of the 1990s, organic agriculture has become much more specialized, and crop rotations have been simplified in arable farming systems. Current organic cropping systems occupy a continuum in a spectrum of intensification and diversification, characterised by different levels of inputs, crop diversity, and crop management practices. Traditionally, the organic farming systems combined livestock (in general dairy or meat production) and crop production within a relatively closed farming system. These systems are common under Atlantic to sub-continental temperate climates with precipitation over 700 mm year-1. The cropping systems are mainly based on a large share of N-fixing crops of more than 40% of the total area such as grass/clover leys or lucerne, associated with cereals, silage maize or root crops in a long term rotation of 8 to 11 years. In order to make maximum use of the large quantities of nitrogen released following forage legumes incorporation, crops with high N-demand such as spring or winter cereals are usually grown after these crops. Silage maize or root crops (potatoes or sugar beet) grown at a less favourable position in the crop rotations receive animal manure in large quantities. Diseases are usually prevented by the crop diversity within the crop rotation and the use of robust varieties. Weeds are prevented by crop rotation, preventive measures in the cultivation (e.g. ploughing) and curative measures during growth (e.g. comb weeder).

In the last two decades, farming systems have progressively increased their share of grain crops in the organic cropping systems. The poor profitability of leys has diminished their importance while high premium for cereals and root crops have encouraged their cultivation. Current rotations consist of cereals, grain legumes, root crops or field vegetables, and annual leys. As organic markets for new crops develop, crops such as sugar beet and oilseeds may be grown more widely. Some farmers also invest in root crops or field vegetables requiring heavy investments but currently providing high net margins.

Irrigated organic farms are typically found in Mediterranean or Continental climates with regular water deficits (precipitation < 700 mm year-1). These cropping systems are based on a balanced proportion of mostly irrigated spring crops, such as maize, sunflower, soybean or pea, associated in crop rotations of 4 to 6 years with winter cereals (i.e. wheat, barley, triticale). The crop rotations contain large proportions of more than 30% of N-fixing legumes as sole crop or intercrop.

Figure 14 illustrates examples of diversified crop rotation under organic farming located in south-eastern France. When irrigation is not available, a typical rotation of 12 to 14 years in pre-mountainous areas is lucerne - winter wheat - secondary cereals - grass clover mixture - winter wheat. A second type of non-irrigated rotation of 8 to 10 years is rather found in plain areas with lucerne – and a combination of maize – soybean - winter wheat. Winter cereal crops are generally dominant in the different rotations, particularly winter wheat. This system is generally less dependent on inputs and valorises forage legumes as green manure and cover crops during intercrop periods to control weed infestation and to reduce mechanical weeding. It also integrates in some cases temporary grasslands, particularly in zones where livestock is still present and where forage could be used to feed animals. Information about other different crop rotations in organic agriculture in France can be found in ITAB (2011).

If access to irrigation is provided, typical crop rotations are based on a short rotation of 3 to 4 years with soybean-winter wheat-maize (which is sometimes repeated a second year) (Figure 14). In such a rotation, winter wheat may profit from the crop residues of the previous leguminous crop. Spring and winter crops, and irrigated and non-irrigated crops are grown alternately. Nevertheless, such a crop rotation is very dependent on inputs. It gives a high degree of efficiency regarding irrigation, but also generates a high demand in nitrogen for wheat and maize, and difficulties to mitigate weed infestation. The latter is partly managed with soil tillage and mechanical weeding. Such practices may maintain crop productivity but can also degrade soil fertility. Consequently, organic farmers have generally decided to sow a temporary grassland with lucerne or clover after 9 to 12 years to regenerate soil fertility and control weeds. Some farmers diversify the basic crop rotation with sunflower, rye or durum wheat, but these crops are considered less profitable or more difficult to produce because of climate conditions or limited nitrogen fertilisation.

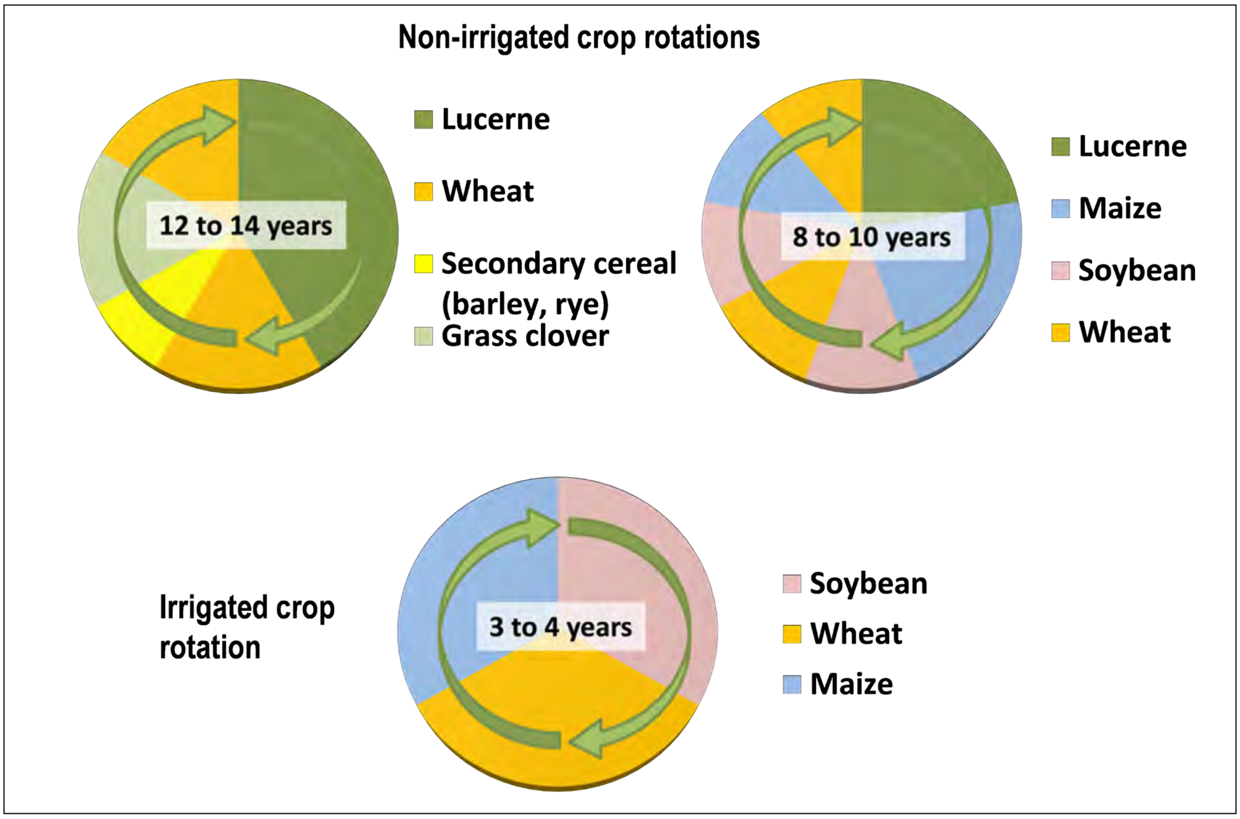

Figure 14. Typical crop rotations observed in organic cereal farms in south-eastern France. With irrigation rotations remain short and are only based on three crops. Longer and more diversified rotations are found when irrigation is not available.

3.2.4 Intercropping and relay intercropping

Intercropping systems are characterised by the simultaneously association of two or more crops. Different spatial arrangements of these species are possible; the intensity and type of interactions will depend on the chosen arrangement and associated species (Malézieux et al. 2008). Interactions can be positive by facilitation, or negative by competition. A simple system is row and strip intercropping where at least one of the associated crops is planted in a row (or strip). The crops are not necessarily sown at the same time and their harvest times may be quite different but they are usually simultaneous for a significant part of their growing periods. Relay intercropping is a different system: two or more crops are grown together only for part of their life cycles, thus limiting interactions between species (Vandermeer 1989). Other categories such as agroforestry (see below) with associations partially composed of perennial species are also sometimes considered as intercropping systems.

The intercropping systems are assumed to have potential advantages in terms of land productivity, stability of outputs, resilience to disturbance, and ecological sustainability, even though they are generally considered harder to manage (Vandermeer 1989). An important issue is to manage competition for light, water, and nutrient resources between the associated crops (Willey 1990, Ong 1995, Van Noordwijk et al. 1996). Intercropping generally improves of resource use efficiency such as the use of radiation (Sinoquet and Caldwell 1995, Ozier-Lafontaine et al. 1997). Different types of facilitation may be observed when one of the associated crops offers a service to the other, e.g. increase of earthworm density when wheat is associated with a clover grass (Schmidt et al. 2003), mitigation of weed infestation due to better competitivity and higher resource use efficiency in intercropped systems (Hauggaard-Nielsen et al. 2001, 2006), improvement of soil physical structure and soil fertility (Latif et al. 1992, Carof et al. 2007), and decrease of both soil crusting and erosion (Le Bissonais et al. 2004).

Intercropping and relay intercropping in France and Europe

Examples provided here compare three types of intercropping systems combining cereal and legumes under organic regimes (David et al. 2010):

Type 1: Cereals intercropped with grain legumes.
Type 2: Cereals sown inside the established legume.
Type 3: Forage legume undersown inside the winter cereal in spring.

First, cereals may be intercropped with grain legumes (Type 1, Figure 15). The two species have similar patterns and durations of development. Pea and wheat are sown and harvested together. Farmers value equally the yield performance of the two components. A yield advantage occurs if intercropping gives higher yields than growing both the component crops separately. Secondly, cereals may also be intercropped with forage legumes (types 2 and 3). The two species have different crop development patterns. Farmers place a high value on the yield performance of the main cereal crop. Cereals may be sown inside the established legume (Type 2). For instance, in a winter wheat/white clover intercrop, winter wheat is seeded into an already established standing crop of white clover. The supply of N from legumes may improve the cereal's N nutrition. The ability of the legume cover to reduce the risk of soil erosion, N leaching and weed infestation during winter as well as after the harvest of the main crop is increased in the case of a well-established cover. Nevertheless, if the management of the living mulch is not carried out at the respective moments to assure the yield formation of the main crop, competition for resources, especially for light and water, may drastically reduce wheat growth and yield, and quality performance (Hiltbrunner et al. 2007). After the harvest of the main crop, the living mulch can be used as forage for animals, either fresh in the form of grazing or conserved as silage or hay. Type 3 illustrates relay cropping of forage legume undersown inside the winter cereal in spring (Figure 16, Figure 17). Competition for resources induced by legumes may be lower than in the case of living mulch. However, the functions of the legume, namely N supply, ability to reduce N leaching and control of weed infestation, may be reduced during the association. Expected N supply and N leaching decreases are more crucial after the wheat harvest and for the succeeding crop.

Figure 16. Relay intercropping of wheat and undersown clover in south-eastern France. In relay intercropping, leguminous species are often sown some weeks after the crop to reduce the risk of competition between main and cover crops. This mixed cropping assures a supplementary soil cover, in particular after crop harvest. Then it limits nutrient leaching, wind and water erosion, fixes nitrogen, and controls weed infestation (Photo F. Boissinot).

Figure 15. Winter field pea (Pisum sativum) and winter wheat (Triticum aestivum) intercropping in western France. Each species has being sown at half its sole crop density, both species being mixed within the rows (Photo G. Corre-Hellou).

Figure 17. Relay intercropping of wheat and undersown lucerne in south-eastern France. Lucerne is another interesting intercrop to be undersown in cereals and it could be harvested as forage because of its high fodder value (Photo A. Wezel).

Wheat-pea intercrop (Type 1) may induce a positive effect on the cumulative yield (pea and wheat) compared to sole crop situations (Figure 18). The LER (Land equivalent ratio) values were on average 1.3 indicating a yield advantage of up to 30% of the intercrops compared to sole crops. The yield of intercropped wheat reached on average 80% of that of wheat sole crop. Another important effect is that improved by N decomposition from the living mulch. The relay legume undersown at spring time (Type 3) had no effect on yield and little effect on grain quality due to a moderate cover development during the association period. Nevertheless, competition for resources by forage legumes could negatively affect protein content when legume growth was significant before wheat flowering stage. A threshold of associated

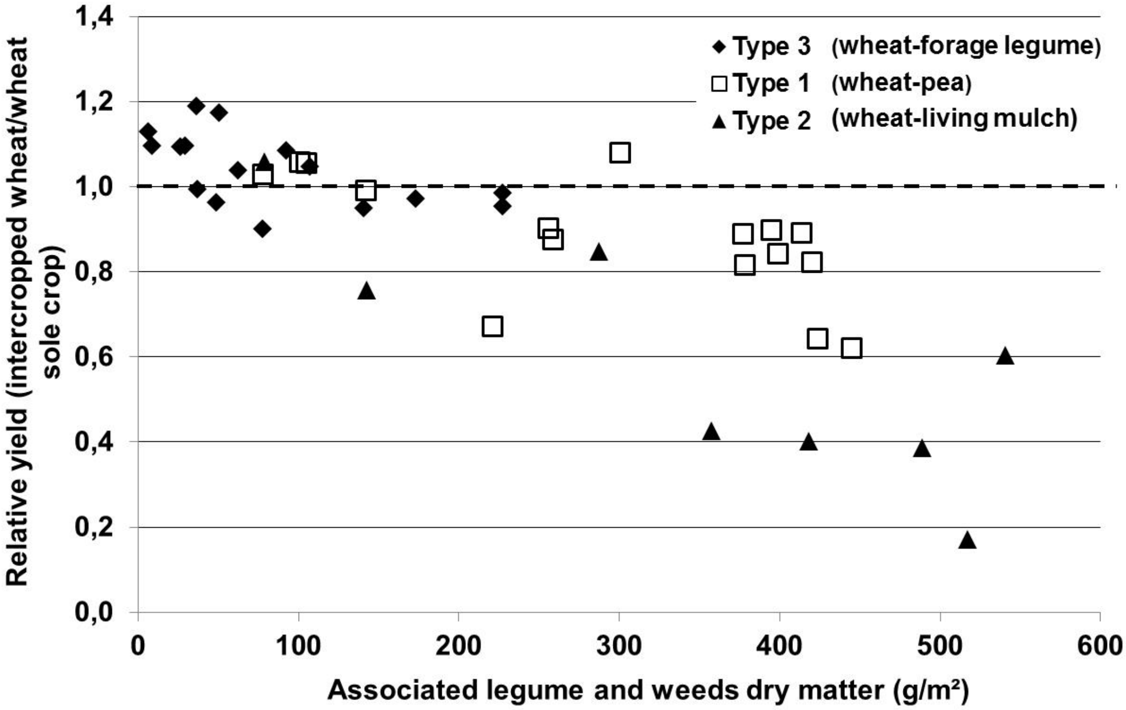

Figure 18. Incidence of three associated legumes on relative grain yield of associated wheat compared to wheat sole crop. On average, higher wheat yield is found when cultivated together with forage legumes. In contrast, average yield of wheat cultivated with a living mulch of white clover is significantly reduced compared to sole wheat cropping (from David et al. 2010).

wheat grain protein content is improved. The optimal use of soil and atmospheric sources of nitrogen in cereal–grain legume mixtures may allow farmers to maintain high production levels and good quality with low external N inputs, and could potentially decrease environmental impacts, particularly through a more efficient use of energy (Pelzer et al. 2012).

In wheat-living mulch of white clover (Type 2) the high biomass of the cover severely reduced wheat yield. The strong competition on resources (water and nutrients) presented by living mulch significantly reduced the grain yield of winter wheat, especially if little was done to control the well-established living mulch. Nevertheless, grain protein content is crop and weeds dry matter could be noticed (around 300 g m^2) beyond which wheat yield was significantly reduced whatever the system. In most situations, intercropping of wheat with legumes seemed to be an efficient way of reducing weed infestation.

3.2.5 Allelopathic plants, and push and pull systems

The introduction of allelopathic plants into crop rotations is a further agroecological practice to reduce pesticide use while providing good crop yields. Allelopathic plants are plant species with the ability to produce chemical compounds which negatively influence the growth and development of weeds, pests or diseases (Weston 1996, Tabaglio et al. 2008, Albuquerque et al. 2011). Allelopathic plants may be used as intercrops or cover crops. They have a direct effect on target organisms by releasing noxious compounds during their life cycle, or an indirect effect through the decomposition of their residues. Some well-known crops such as rye, sorghum or sunflower have a good potential as cover crops because they inhibit weed seed germination and/or development due to the release of root exudates (De Albuquerque et al. 2011). Similarly, Brassicaceous crops negatively impact weeds, pests and diseases through the decomposition of their residues in the soil (Médiène et al. 2011, Ratnadass et al. 2012).

Allelopathic plants do not only have direct detrimental effects on organisms. They can also have repellent or attractive effects and thereby be used to manage pests and diseases. In that case, the allelopathic compounds attract the target organism(s) and the plant actually acts as a "trap" crop (Hokkanen 1991, Shelton and Badenes-Peres 2006). For example, crops can be used as cover crops or intercrops because they stimulate weed germination, thus reducing the soil seed bank (Scholte 2000a, b; Scholte and Vos 2000 cited in Ratnadass et al. 2012). The push-pull strategy is based on repelling or deterring insect pests from crops (push), and then attracting them with trap plants around or even within fields to 'pull' them away from crops (e.g. Khan and Pickett 2004). A classic example of a "push" crop is onions, because, when cropped together with carrot, it directly reduces attacks of carrot fly by releasing deterrent compounds (Uvah and Coaker 1984 cited in Ratnadass et al. 2012).

Although there is a wide range of possibilities to benefit from allelopathic plants, so far, this type of practice has not been widely applied. There is a lack of understanding of the biological processes, and efficiency and results are highly variable depending on local conditions (De Albuquerque et al. 2011, Mediène et al. 2011). Moreover, allelopathic crops can also behave as pathogen-hosts (Ratnadass et al. 2012).

Allelopathic plant management, and push and pull systems in France and Europe

In the last decades the number of experimental studies on the use of allelopathic plants on pest and weed control has increased and potentially efficient ways to use allelopathy in agriculture have been highlighted:

- selection of crop (varieties and cultivars) with strong allelopathic effects,
- use of an allelopathic intermediate crop between two cash crop to suppress weeds,
- plantation of allelopathic plants between rows of a specialized crop, and
- use of mulch composed of allelopathic plants.

However, in practice, it is difficult to disentangle resource competition and allelopathic effects of a given plant species on weed suppression. There is a significant variation of the allelopathic power of a plant species according to species or cultivars and the side effects of the use of an allelopathic plant as intercropping or relay cropping on the main crop (e.g reduction in growth and biomass production, germination inhibition) is still largely unknown.

As a consequence there is still great uncertainty about the predictability of allelopathic activity in different cropping systems (Weih et al. 2008). Therefore despite the increasing number of experimental data and assays, the large scale implementation of allelopathic strategies remains limited in European agriculture.

Several crops with allelopathic effects are still regularly used in agronomic and horticultural cropping systems. In France and Europe, winter rye (*Secale cereal*) is, for example, commonly inserted in a crop rotation and can provide weed suppression for a period of 30 to 75 days depending on soil and weather conditions (Weston 1996). Similarly winter wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), Sorghum (*Sorghum bicolor* and *S. sudanense*) or alfalfa (*Medicago sativa*) are also often inserted in crop rotation and provide a noteworthy weed control service (Bhowmik and Inderjit 2003, De Albuquerque et al. 2011). Clover (*Trifolium* spp.) and sweet clover (*Melilotus* spp.) primarily used as cover crops also appear to have some allelopathic potential (Weston 1996).

The grass false barley (*Hordeum murinum*) is an allelopathic plant that is planted between rows of a specialized crop (i.e. vine) to ensure weed management. Concerning mulch made from allelopathic plants, we can observe the use of rye residues for their herbicidal activity. Perennial ryegrass, red and white clover are commonly used as living mulch, partly for significant allelopathic activity.

Very few cases of large scale applications of push pull strategies in European agriculture exist. Indeed push pull strategies have mainly been implemented in sub-Saharan Africa where farmer access to chemical control products is more challenging. The most famous example is the use of *Desmodium* ("push") in between the rows of maize, and Napier grass (pull) on borders to control stemborers and *Striga* weeds.

3.3 Redesign and diversification: integration of production systems

As mentioned before under 3.2, the implementation of some practices needs a redesign of cropping or production systems because these practices cannot simply be slightly modified or adapted to certain conditions. In most cases a redesign is needed when the objective is system diversification. This section provides examples of practices which include a diversification and redesign of production systems.

3.3.1 Integration of timber, fruit, or nut trees on cropped fields

Different types of agroforestry practices can be considered as agroecological practices since they reduce nutrient leaching, conserve soils, increase diversity of the production system, and produce complementary wood, fruits and nuts for various uses (e.g. Buck et al. 1999; Eichhorn et al. 2006, Mosquera-Losada et al. 2009). Often, agroforestry systems integrate crops and timber plants. However, there are also more specialised systems that focus on fruit or nut tree integration, and forage trees. In some cases, these fruit or nut tree systems are coupled with extensive grazing of grassland below or between the trees. Advantages of agroforestry systems are increased land productivity, yield diversification, better use of resources on a given spatial and temporal scale (water, nutrients, solar radiation), reduction in nutrient losses from agricultural land, increasing carbon sequestration, enhanced biodiversity, and reduced soil losses (Eichhorn et al. 2006, Rigueiro-Rodrígues et al. 2009a). Constraints for agroforestry systems are higher management needs, loss of cropped land for the main crop, often a higher labour demand, and competition of trees with adjacent crops for water, nutrients, and light.

Integration of timber, fruit, or nut trees on cropped fields in France and Europe

In Europe, there are different agroforestry systems that integrate crops and woody plants, sometimes in combination with grasslands (Mosquera-Losada et al. 2009, Rigueiro-Rodrígues et al. 2009b). Mixed systems of agriculture combining trees and crops have formed key elements of European landscapes throughout historical times (Eichhorn et al. 2006). Many of these systems still exist today, but in general a strong decline in numbers and area can be perceived in the last 50 years.

In France, fruit tree meadows (pré-vergers) remain particularly abundant in northeast France (Eichhorn et al. 2006). The fruit trees often have a dual purpose with timber and fruit production, especially apple, pear and walnut trees. In the regions of Périgord and Dauphiné some walnut plantations are intercropped during the early years of the trees (Eichhorn et al. 2006). In the Dauphiné area, trees are grown for about 30 years, and crops are cultivated during the first 5 to 15 years (Liagre 1993 and Mary et al. 1999 cited in Eichhorn et al. 2006). Crops vary from maize and other cereals (Figure 19), sorghum, soybean, rape seed, and sunflower, to tobacco, lucerne, lavender, and bush fruits. Around 20 % of these walnut plantations are intercropped (Dupraz and Newmann 1997 cited in Eichhorn et al. 2006).

Figure 19. Walnut wheat agroforestry system, south-eastern France. This agroforestry system is mostly found in extensively used agricultural landscapes in France. Main valorisation of tree products is walnut oil and nuts (Photo A. Wezel).

The fruit tree meadows are also well-known in Germany (Streuobstwiesen), in particular in the federal state of Baden-Württemberg in southern Germany, but they have strongly declined since 1950 (Herzog 1998, Herzog and Oetmann 2001). The most common fruit trees are apple, pear, plum, sweet cherry, and walnut (Figure 20). In rarer cases, the meadows under the trees are grazed. Trees are planted at an average density of 20-100 stems per hectare. Typically they have logs 1.6 to 1.8 m in length (Herzog 1998). Fruit tree meadows can also be found in Switzerland, Spain (Arboles en disemiando, in northern Spain pomaradas) and Poland (Herzog and Oetmann 2001). Approximately 1 million ha of fruit tree meadows exist in 11 European countries (Herzog 1998).

Mixed crop and fruit tree systems have almost completely disappeared. In Germany, for example, the silvoarable system still exists consisting of paired rows of fruit trees with crops in-between (Streuobstäcker), but on very limited areas, and only in very small fields. Olive groves intercropped with durum wheat exist only on some 10 ha in France, but on 100,000 ha in Italy (Dupraz and Liagre 2011).

Figure 20. Fruit tree meadow in autumn in southern Germany. They consist mainly of scattered apples trees, often accompanied by some cherry, pear, plume, and walnut trees. Normally the meadows are mown two to three times per year. In rare cases they are grazed by sheep or goats. The apples are mainly used for fruit production, and only secondarily for fruit juice production (Photo A. Wezel).

The fruit tree meadows of central and northern Europe are replaced in southern Europe by systems which incorporate grape vines (Eichhorn et al. 2006). In these systems trees are no longer the focal element, but provide the function of mechanical support for the grapevines (Meiggs 1982 cited in Eichhorn et al. 2006). Different types of this tree-grapevine system can be found, but only on much reduced areas. In France, for example the system known under the name Joualle is composed of rows of grapevine with peach, walnut and olive trees, and in some cases the trees were used to support the vines (houtain) (Eichhorn et al. 2006). Similar systems exist also in Greece, Italy (e.g. Po Valley, Campania), and Spain with integrated olive, walnut, various oak species, and wild pear (Figure 21, Figure 22). In Italy, these vine grape systems are sometimes intercropped with fodder legumes (Figure 23), and wheat (Figure 24) (Bertolotto et al. 1995 cited in Eichhorn et al. 2006). A system with pine tree – grapevine intercropping from France is shown in Figure 25.

Figure 21. Vines-walnut trees-fruit trees agroforestry system, central Italy. Trees are partly used to support the vines. This traditional agroforestry system is today only rarely found (Photo A. Wezel).

Figure 22. Grape vine-olive trees-walnut trees agroforestry system, central Italy. Different tree species are planted in the rows of vines, but with a sufficient distance between them that they do not overly shade the vines (Photo A. Wezel).

Figure 24. Agroforestry system consisting of grapevine, fodder trees, and cereal cropping, central Italy. This specific system integrates different fodder tree species and vines in the same row, and in-between rows cereals are cropped (Photo M. Casagrande).

Figure 23. Walnut-lucerne agroforestry system, central Italy. The lucerne area between walnut rows are mainly harvested for fodder, but can also be grazed by livestock (Photo A. Wezel).

Figure 25. A system of grapevine and lines of pine trees in southern France. This agroforestry system consists of rows of pine trees which are inserted between several rows of vines (Photo W. Trambouze).

Mixed fruit tree-vegetable systems are also found in Europe. In the province of Languedoc-Roussillon, southern France, a modern intensive agroforestry system combines peach trees with intercropped vegetables (Eichhorn et al. 2006). Small intercropped orchards with fruit trees and vegetables exist in northern Spain (INE 2002 cited in Eichhorn et al. 2006), as well as throughout the Mediterranean region with almond, peach, apricot, olive (Figure 26), and walnut trees (Eichhorn et al. 2006). A system still important in Italy (mainly Campania), although in decline, is walnut-vegetable intercropping, often mixed with hazelnut. The greatest expanse and diversity of fruit producing silvoarable systems is found in Greece. Depending on the region, pears may dominate, intercropped with vegetables, cereals, or tobacco, whereas walnut or mulberry is preferred in other regions

Figure 26. Olive tree agroforestry system with undergrowth of leguminous species and grassland in Sardinia, Italy. This type of agroforestry system allows different crops to be combined on the same field. Resource use efficiency is increased because of different root systems, so better nutrient cycling can be expected. Legumes fix nitrogen, and below tree species they cover the soil and prevent wind and water erosion (Photo M. Casagrande).

Timber tree-crop systems are other important systems in Europe. In France, intercropping of poplar with cereals, maize or asparagus during the first three years is found on larger areas (Eichhorn et al. 2006, Dupraz and Liagre 2011). This system is also important in northern Italy, in particular in the Po Valley, with maize, soybean and cereals grown between the rows the first 2 years of a 10-year cycle. To a much lesser extent, similar systems are found in the United Kingdom and the Netherlands. Systems with tree rows consisting of black locust, ash, oak, or maple are reported in France and the United Kingdom (Eichhorn et al. 2006). Intercrops are normally cereals or pulses.

Landscapes with the presence of scattered oaks and contiguous arable and pastoral associations are well known in the Iberian Peninsula. The dehesa system in Spain is probably the largest agroforestry system in Europe (Eichhorn et al. 2006, Moreno and Pulido 2009). The oak trees have been selected for acorn production for raising pigs. The space between the low density scattered trees is mainly used as pasture for pigs, but also cattle, sheep and goats. On smaller areas, it is also cropped with cereals, fodder crops, or sunflower. In Portugal, this system is found under the name montados. Similar systems also occur in Greece and in Sardinia (Eichhorn et al. 2006).

Other silvoarable oak systems, but without pastures, are also widespread in Greece with mainly cereals grown between the scattered trees, but also tobacco, sunflower and fodder crops. Comparable systems persist in marginal areas of central and southern Italy and Sardinia (Eichhorn et al. 2006).

3.3.2 Mixed crop-livestock systems integration at farm or landscape level

Integrated mixed crop-livestock systems are defined as farming systems having a wide range of interaction between crops and livestock on the farm. Crops and livestock are managed to enhance natural biological cycles. Crops provide straw and/or grains for the animals' keep and feeding, livestock manure provides nutrients for crop fertilisation. The animals' nutrition is balanced thanks to grazing on pastures, complemented by fodder legumes, and grains. Ecological benefits due to rotations between crops and pastures are widely acknowledged such as soil biological activity and fertility enhancement of fields, nutrient recycling, and erosion reduction (Wilkins 2008, Ryschawy et al. 2012).

In the last decades a specialization to either cropping or livestock systems has strongly developed, and often even led to a complete separation of the two. In the remaining mixed crop-livestock systems, intensification is still increasing in many livestock production systems (FAO 2006). Recent publications relate the constant predominance of industrial intensive systems in meat, milk and egg production, especially in northern pastures, meadows, and croplands. This is even the case in southern less-favoured regions of Europe and Northern America where some more traditional pastoral systems are disappearing and others are replaced by semi-intensive livestock systems (Caraveli 2000, De Rancourt et al. 2006, Escareño et al. 2013). Rangeland degradation, lack of income, and workload of farmers are major reasons for intensification in these regions.

A recent FAO report states that "the largest and fastest growing population lives in towns and cities, and its demand for reasonably priced meat, milk and eggs has been a strong inducement to intensify livestock food systems so that economies of scale can be realized and market chains managed efficiently. [...] There are no technically or economically viable alternatives to intensive production for providing the bulk of the livestock food supply for growing cities" (FAO 2011). When a central place is given to energy and nutrients savings, to environmental pollution reduction, biodiversity conservation, and competition for cereals for human consumption is taken into account (FAO 2006), then cereals (mainly maize) and soybean imports to feed animals to achieve high yields of milk and meat appear to be less favourable, compared to systems based on using a wide diversity of rangelands, and systems that locally integrate diversified crop rotations. But the capacity of these alternative systems to substitute for intensive systems remains a major challenge in different parts of the world.

Here we will present only two agroecological livestock practices in relation to mixed crop livestock systems: i) substitution or reduction of non-locally produced cereals and soybean, and ii) the re-integration of natural and semi-natural rangeland in certain livestock systems. Other agroecological practices in livestock systems can be found in Dumont et al. (2013).

3.3.2.1 Substitution of non-locally produced maize and soybean in integrated crop-livestock systems

To promote ecosystem-based and not fossil fuel-based, fodder import systems, alternative fodder and proteins sources are urgently needed to partially or completely replace cereals and soybean which are presently the most imported fodder resources. Favouring grass-based systems with large proportion of nitrogen fixing legumes are known to strongly increase farm self-sufficiency in relation to fodder resources, and to optimize nutrient cycling and energy use (Soussana et al 2011, Veysset et al 2011). Mixed crop-livestock systems, e.g. cropping systems including temporary pastures in the rotation for grazing animals are

commonly described as being the most efficient in resources exploitation because of the re-use of wastes, the improvement in soil fertility, and the low levels of external inputs such as fertilisers (Ledgard et al 2009, Mondelaers et al 2009).
A lot of studies highlight that pasture-based dairy systems have shown that they can be more profitable than systems with animals housed year round and fed with a mixed ration based on cereals and soybeans (Benson 2008). Pasture-based dairy systems often succeed in obtaining higher milk prices due to niche markets for example in the United-States or Europe (Benson 2008). But, confinement systems remain more profitable when the standard milk price is high, and pasture-based systems can even be unprofitable with respect to returns to labour.

Even profitable, pasture-based systems show lower milk yield or meat productivity per cow. Thus, these systems will probably be insufficient to cover the increasing global demand in meat and milk. Increasing the stocking rate in pastures might be a good way to enhance the productivity and profitability in a pasture-based dairy-system, but the environmental effects have to be carefully evaluated. Recent projects show that some pasture-based systems already use a lot of nitrogen inputs (e.g. about 250 kg N per ha, Institut de l'Elevage 2006), which implies a high risk of nitrogen loss into the environment.

A lot of techniques can increase the efficiency of a pasture-based system, and therefore reduce the disparity in production compared to confinement systems:

- the improvement of grasslands by increasing diversity (Lüsher 2008)
- the maximisation of dry-matter intake thanks to sward height management (Maxwell and Treacher 1987, Wright 1988, Mayne et al. 2000)
- the preference for breeds well-adapted for grazing (White 2002)

Grasslands management and performance can be improved by using more intensive temporary grasslands combined with permanent natural grasslands. Various perennial species cropped in temporary grasslands can provide animals with valuable food for a long period. In particular clover, lucerne, orchard grass (*Dactylis glomerata*), *Festuca* spp., *Bromus* spp.are well-known as high yielding or high fodder quality species. The selection of productive varieties with drought resistance or frost resistance qualities (Thomas 1997) has lengthened the period of use of grasslands in Northern regions. Some grasses like ryegrass were selected with higher water soluble carbohydrate concentrations and a balanced ratio of ruminal nitrogen and energy, resulting in better nitrogen assimilation, lower nitrogen excretion, and higher milk yields (Miller et al. 2001). Some varieties of legumes such as clover or lucerne have also been developed to decrease nitrogen inputs and to increase protein intake at grazing without reducing grassland productivity. It is still not possible to predict the composition of the intake-diet of animals grazing multi-species swards, but performance can equal swards with N inputs. For example, a mix of 70% grass species and 30% white clover without fertilisation can produce as much as all-grass swards receiving 200 kg N fertiliser per ha per year (Morrison 1981). When white clover is incorporated, nutrient supply and protein intake showed an increase, resulting in higher performance in milk yield (Clark and Jans 1995, Davies and Hopkins 1996).

Optimised sward height management can maximise intake at grazing. Highest pasture-based farming productivity is obtained when pasture managers target specific sward heights from the beginning of spring to early summer (Maxwell and Treacher 1987, Wright 1988, Mayne et al. 2000). Because of changes in grass growth, the turnout between paddocks should be managed to prevent overgrowth in spring, leading to a reduction of nutritive value and intake, and conversely the turnout should be managed in late spring to maintain enough grass for early summer.

When applying the above mentioned techniques and practices, a pasture-based dairy Holstein cow system can achieve 7000 kg per cow and year (Kennedy et al. 2002, Horan et al. 2005, Delaby et al. 2009), with just 500 kg of concentrate per cow.

The efficiency of the different ruminant breeds varies greatly. Jersey cows appear to be more efficient than Holstein cows for example (Grainger and Goddard 2004, Mackle et al 1996). Therefore, Holsteins are crossed with Jersey (New-Zealand, Ireland) in countries with a lot of pasture-based systems. Although cows with high genetic merit for milk yield (around 10,000 kg/cow/year) can produce even more milk in pasture-based systems than locally adapted breeds (Dillon et al 2003, Horan et al 2005, McCarthy et al 2007), they have difficulty in being fertile (Pryce et al 2004), and maintaining a good body condition (Buckley 2000). As a consequence, highly productive cows show higher culling rates (Dillon et al 2003, Evans et al 2006), giving evidence that locally adapted breeds for grazing are better suited for efficient pasture-based system. These local breeds produce less milk but they provide an important second income thanks to their production of meat.

Examples of substitution of non-locally produced cereals and soybean in mixed crop-livestock systems in France and Europe

An example of mixing different breeds with different production objectives in pasture-based livestock production systems is illustrated in Figure 27. The herd is composed of Holstein cows (highly productive milk cows) and Normandy cows (bred for milk and meat production). Normandy cows are more efficient during the grazing period, and so start lactation in the beginning of spring. Holstein cows are more efficient in winter when fed with highly nutritive forage and concentrate, so they calve in autumn. The sward height is kept low to prevent the decrease in daily intake that occurs when the sward is too high, and paddocks are proportioned and stocked with optimal livestock numbers to prevent grass wastes. These temporary grasslands alternate with crops which benefit from the rotation. This integrated crop-livestock system shows high profitability, and ecological benefits thanks to reduced nitrogen inputs, reduced use of concentrates, complete self-sufficiency in starch source for livestock, an average milk yield of 7000 kg per cow and year, and meat production.

Figure 27. A mixture of cow breeds on summer grazing paddocks in Northern France. Mixing Holstein and Normandy cows is beneficial because the two different breeds have different lactation periods and different forage quality requirements in different periods of the year. Therefore pasture resources can be more optimally used. Paddocks are proportioned and stocked with optimal livestock numbers to prevent grass wastes (Photo A. Letort).

3.3.2.2 Integration of natural and semi-natural rangelands into mixed crop-livestock systems

Pastoral systems use 25% of the world's land surface and provide food for around 200 million people (Degen 2006). They are exemplary for their acceptable impact on ecosystems if overgrazing is prevented due to a holistic management. They are also judged to have a low impact on water and atmosphere (few greenhouse gas emissions). Their capacity to produce food from rangelands with few or no inputs has mainly placed them outside cropland areas. A lot of such pastoralists suffer from low income or even poverty, because products from pastoralism are not able to compete with product prices from intensive livestock production. Moreover, they generally do not benefit from higher prices in acknowledgement for this typical type of extensive traditional farming.

The capacity of shrubby and woody rangelands to provide cheap and adapted food in particular for small ruminants during hard times has always motivated extensive livestock keepers to include rangelands in the grazing planning in addition to grasslands. Nevertheless, more and more rangelands in Europe are not grazed anymore (De Haan et al. 1997). This can be explained by the degradation of rangeland ecosystems (Walker 1995), with extreme situations of invasion by exotic plants, or soil erosion leading to degradation. Poorly adapted management is a major factor, mainly because a lot of livestock systems were turned into intensive foraging systems, leading to overgrazing or undergrazing situations (De Haan et al. 1997, Castel et al. 2011). The re-use of abandoned rangelands can be a way to reduce the stocking rate on intensified grasslands, especially in southern Europe. The intensification on these intensified grasslands, strongly supported by irrigation and fertiliser inputs, endangers local environments and does not suit rangeland browsing, the latter being of significant ecological importance (Caravelli 2000). The following factors have to be taken into account when re-using abandoned rangelands: i) guaranteeing suitable energy intake for small ruminants when including rangelands into modern livestock production systems, ii) maintaing of ecosystem stability of rangelands, and iii) re-valorising already degraded rangelands.

Wooded rangelands or shrublands are patchy ecosystems with thickets of shrubs, young trees, adult trees, and sometimes isolated grasslands (Bakker et al. 2004). Large and soft leaves of some woody plants are highly nutritive, but some woody plants are not attractive because of spines or toxic compounds (Bergman et al. 2005), and some species are of low nutritive value (Meuret, 1994). But small ruminants can compensate for low energy density of heterogeneous pastures or shrublands by increasing their intake of dry matter and nutrients (Meuret 1996, Provenza et al. 2002). An optimal shepherded circuit can maximise intake in shrublands (Meuret 1996). The circuit is based on positive digestive interactions provided by the different patches, in a manner that promotes high dry matter intake. Optimal shepherded circuits enable the consumption of low-palatable plants and promote ecosystem stability. But, because shepherding requires a lot of time, this practice has become rare.

An alternative to shepherding is the paddock approach: animals are fenced for several days, and removed after a certain time. But the paddock approach jeopardizes ecosystem stability as small ruminants prefer plants of high nutritive value and tend to under-browse low-palatable plants (Provenza 1996). In this case, intensive stocking rates can enhance the use of these low-palatable plants. Most deciduous plants regrow after browsing (Hester et al. 2004, Krause and Raffa, 1996), but under overly intensive conditions the most attractive plants disappear, which can lead to soil erosion, and exotic species invasion (McIntyre and Lavorel 1994, Pettit et al. 1995, Yates and Hobbs 1997). Low-intensity browsing is associated with high biodiversity (Olff et al. 1999, Bakker et al. 2004, Bakker et al. 2006, Smit et al. 2006) but often leads to invasion by low-palatable species. A rotating paddock-by-paddock approach may be the best way to maintain the shrub cover and productivity, and to enhance energy intake, but less is known about how plants react to browsing when subjected to different short intense browsing sequences.

Some shrublands are too degraded to provide suitable energy intake for livestock for several months. Some are invaded by toxic plants, and others are completely covered by shrubs and trees (Van Uytvanck et al 2010). In this case, goats are well suited for managing these rangelands. Goats browse more woody plants than sheep or cattle. Goats can extract more nutrients from tree leaves, and they can better tolerate toxic compounds thanks to an intense detoxification process in their liver (Wisnewski et al. 1987).

A lot of meat sheep combined with meat or dairy goats have been turned into sheep specialized systems. And dairy goat specialized systems have turned into intensive or semi-intensive systems, or foraging systems devoted to active self-marketing via direct selling (Escareño et al. 2013). These systems are based on minimal time spent for rangeland fencing, animal moving, and outdoor milking. Local projects are emerging in Europe thanks to public subsidies (Van Uytvanck et al. 2008), but few small ruminant systems have re-used degraded rangelands.

Examples of integration of natural and semi-natural rangelands into mixed crop-livestock systems in France and Europe

Examples provided here concern different sheep and goat systems using wooded rangelands either in winter or summer, including transhumance to forest areas. The following yearly cycle is characteristic of a transhumance system where sheep use woody rangeland in winter. In general, in early spring (March) lambs are born. Then ewes spend one month in a stable to secure a good supply of nutrients during the early lactation period. After one month, ewes graze grass-dominated pastures with their lambs. When the drought period starts in late spring or early summer, ewes are moved to forest areas (Figure 28). Most of the lambs are sold before the transhumance to forest areas. Ewes keep on grazing in forest areas until November, and then they are moved to Mediterranean shrublands in winter until the next calving season in March. In this traditional agro-silvopastoral system, the production costs of lambs are very low, and compensate for often low market prices (Papanastasis 1996).

Figure 28. Sheep on transhumance to forest areas to find green vegetation in summer (Southern France). Forest areas are grazed until November, and then sheep are moved to Mediterranean shrublands in winter before they return to grass-dominated pastures with their lambs in spring (Photo A. Letort).

A system where woody rangelands are used in summer can also be found in southern France (Figure 29). In this off-seasonal productive dairy goat system (700 kg per year and goat) with births in September, the end of lactation and the dry period of goats should be as cheap as possible in terms of production costs. Furthermore, goats should be fed with high value fodder to maintain digestive capabilities during pregnancy and for early lactation. Goats graze a mixture of natural permanent and temporary grasslands composed of a wide range of species from September to June: dry grasslands in early spring, humid grasslands in late spring, productive grasslands in spring, and dry temporary grasslands sown with drought-resistant species in late spring and early autumn. In July and August, grasslands are replaced by woody shrublands. This pasture-based dairy goat system increases profitability, also due to decreased irrigation and less nitrogen inputs on pastures in spring thanks to the re-use of woody rangelands, including degraded ones. Similar systems are also reported in the USA (Hart 2001)

Another example of a dairy goat system which uses a wide range of pastures and rangelands can be found in more humid northern France (Figure 30). Goats

Figure 29. Goats browsing tree and shrub leaves in summer in southern France (left). Flocks of goats moving to woody rangelands (right). The use of grass pastures and rangelands with shrubs and trees allow different, but well-suited fodder resources to be used for goats (Photo A. Letort).

Figure 30. Dairy goats system using a wide range of rangelands in more humid northern France. Goats stay outside all year long. In winter, goats browse also nearby semi-evergreen shrublands. The mobile milking machine allows keeping the livestock also on remote pastures or rangeland (Photo A. Letort).

stay outside all year long. In winter, once dried-off, goats browse in semi-evergreen shrublands nearby. From spring to autumn, grasslands provide enough dry-matter and nutrients for an average milk yield of 500 kg per year and goat. The small herd of about 30 dairy goats are milked daily by a mobile machine. Thus goats can remain even on more remote pastures. Income is mostly generated by local marketing of on-farm made cheeses.

A final example of using alternative rangelands for livestock for part of the year is taken from grazing in vineyards (Figure 31). In this system, sheep graze after the grape harvest in vineyards with vegetation cover between the grapevine rows. In exchange, sheep enhance grapevine nutrition via faeces. Such a system allows the combination of two quite different productions on the same land.

Figure 31. Example of a vineyard in southeastern France grazed by sheep after the grape harvest. Due to vegetation cover erosion risk is reduced in the vineyard. The vegetation cover provides fodder for sheep, and sheep provide nutrients to grapevines via faeces (Photo A. Letort).

3.3.3 Integration of semi-natural landscape elements at field, farm or landscape scale

Different types of landscape elements such as hedgerows, thickets, grass strips, and ditches can play an important role for agriculture. Depending on their management and their functionality, they can help to increase biological control of pests, support pollinators, and protect against wind and soil erosion and against surface water contamination.

3.3.3.1 Integration of semi-natural landscape elements for biological control

The integration, or re-integration, of natural or semi-natural landscape elements such as hedges and vegetation strips, either in or around the field (Figure 32), or at a landscape scale for improved biological control has become more recently an issue. These landscape elements have good potential in providing habitats and overwintering sites as well as resources such as alternative prey for beneficial insects or other pest predators (Figure 33), thus reducing the need for pesticide applications. Due to higher natural plant diversity and flowering these habitats are also important in providing resources such as nectar and pollen which are important for different beneficial insects during certain periods of the year, and certain periods of their life cycles (Figure 34).

Figure 32. Landscape elements surrounding a cereal field, south-eastern France. Woody landscape elements can have different functions such as protection against wind and water erosion, habitats for beneficial insects and pollinators, production of timber and firewood, ecological corridors in agricultural landscapes, and biodiversity conservation (Photo A. Wezel).

Figure 33. Conservation biological control: Preservation or creation of habitats near fields or in the larger landscape for reproduction, over-wintering, or shelter during different phases of the life-cycle of beneficial insects which then can control pests. The present photo shows a ladybird beetle, a natural predator of aphids, on organic wheat in south-eastern France (Photo A. Wezel).

In most cases the diversity of habitats within landscapes greatly affects communities of herbivores and their natural enemies within an agricultural crop (Altieri and Nicholls 2004; Gardiner et al. 2009). The majority of studies show that herbivore density and crop damage decrease with increasing proportions of non-crop habitats in the landscape. For example, Thies et al. (2003) found decreased plant damage and increased larval parasitism in structurally complex landscapes. Östman et al. (2001) showed that regardless of conventional or organic farming practices, early season establishment of aphids was lower in landscapes with abundant field margins and perennial crops. Altieri and Nicholls (2004) and Obrycki et al. (2009) found that the introduction of flowering plants as strips within cropped fields enhances the availability of pollen and nectar, necessary for optimal reproduction, fecundity and longevity of many natural enemies of pests, leading to greater abundance of aphidophagous predators and reduced aphid populations.

Not only is the diversity of these elements or habitats very important for obtaining positive effects from landscape elements and natural habitats on pest control, but also the percentage of land they cover at the field, farm or landscape scale. Some indications can already be given, but this must also be seen site-specific in relation to the type of pests and the type of habitats needed for their natural enemies. In general, With and King (1999 cited in Gardiner et al. 2009) as well as Thies and Tscharntke (1999) showed that search success of natural enemies and parasitism rates declined when the non-crop area fell below 20%. In addition, the impact of landscape structure is dependent not only on the total amount of suitable habitats within landscapes, but also on the spatial arrangement of habitats as herbivorous pests and their natural enemies vary in their capacity for dispersal (Gardiner et al. 2009). In their review paper, Tscharntke et al. (2007) clearly state that the enhancement of biological control needs a landscape perspective and consideration of possible interacting effects between the landscape context and local habitat quality.

Figure 34. Flower resources for beneficial insects (hoverflies, beetles), central Germany. Higher plant and habitat diversity is important to provide resources such as nectar and pollen which are important for different beneficial insects during certain periods of the year, and certain periods of their life cycles (Photo A. Wezel).

3.3.3.2 Integration of semi-natural landscape elements for pollination

Different types of landscape elements are also of high importance for crop pollination. Due to higher natural plant diversity and flowering they attract pollinators and host them outside the crop flowering period (Ricketts et al. 2008). A decline in pollinators has also been observed in several European countries (Biesmeijer et al. 2006, Potts et al. 2010) putting many pollinator-dependent crops under threat from a deficit in pollination, and consequently significant yield reductions (Kluser and Peduzzi 2007, Aizen et al. 2008, FAO 2008). Among the different drivers identified for pollinator decline are habitat erosion and intensive use of pesticides (Osborne et al. 2001, Thomas et al. 2004, Kluser and Peduzzi 2007, Potts et al. 2010, van der Valk et al. 2013).

In this context, semi-natural landscape elements can help to support pollinator populations in crop fields and in surrounding environments (Kluser and Peduzzi 2007, Ricketts et al. 2008, Hodgson et al. 2010, Kjolh et al. 2011). First, they can have direct effects on pollinator presence in agroecosystems and on pollinator population dynamics through the provision of complementary food and nesting sites for reproduction and over-wintering. Crop fields, especially monoculture plots, usually provide abundant (despite not being varied) food for their pollinators during the crop flowering period but are generally poor quality habitat the rest of the year. The presence of vegetation strips or hedgerows containing different plant species (Figure 35), especially plants with flowering periods out of synchrony with the one of the crop, supply pollinators with more diverse and temporally more available food sources. In addition, such semi-natural elements potentially provide varied nesting sites: for example non tilled soil areas on field margins for miner bees (Figure 36, Figure 37), hollow plant stems, abandoned insect burrows or snail shells in hedges for mason bees (Figure 37) (Potts et al. 2005, FAO 2008).

Secondly, the integration of semi-natural elements might also have an indirect positive effect on pollinator presence and activity in the crop fields in relation to pesticide use. Indeed, pollinators come in contact with pesticides through several potential routes: direct exposure when pesticide applications overlap with pollinator foraging activities in the field, or exposure through pesticide residues in pollen and/or nectar (Künast et al. 2011, van der Valk et al. 2013). Such exposures to pesticides even at sub-lethal doses can poison the pollinators, and impair their reproduction and their ability to forage for food or make nests (Desneux et al. 2007, Potts et al. 2010). Here, semi-natural elements might also allow the conservation or re-establishment of healthy and diverse pollinator populations. In general, pollinators have a greater chance of being immediately present, active and numerous enough in the field when crops are blooming to ensure efficient pollination when semi-natural elements are sufficiently present in agroecosystems.

Figure 35. A Hedgerow along the side of a rapeseed field. The structurally rich hedgerow provides different habitats for pollinators as well as food resources via different species with different flowering periods during the year (Photo H. Mouret).

Figure 36. Non-tilled soil strip. This type of habitat provides nesting sites for numerous miner bee species (Photo H. Mouret).

Figure 37. Different types of bee nests. Such types of bee nests can be found in field margins and in hedgerows, or similar habitats (Photo H. Mouret).

3.3.3.3 Integration of semi-natural landscape elements for erosion control

The in-field and around-field landscape elements also protect against wind and soil erosion (Figure 38) and against surface water contamination (Baudry and Jouin 2003, Wu et al. 2010). In addition, they generally assure biodiversity conservation in agricultural areas.

The major constraints of these landscape elements are that they reduce the cropped area and potential food production, and have to be managed by farmers. In addition, they may also harbour habitats for pest species, and the efficiency of natural pest control may vary considerably. The current challenges are to preserve existing landscape elements and to re-establish or increase introduction into present agroecosystems and agricultural landscapes as many landscapes have been "cleaned" in the last decades to allow larger and more homogenous areas to be cultivated.

Figure 38. Soil erosion on different fields at the beginning of the growing season in south-eastern France. Lack of soil cover with cover crops or mulch, or non-existence of landscape elements across fields induced important soil loss after strong rainfall events (Photo B. Sarrazin).

Examples of integration of semi-natural landscape elements in France and Europe

Many examples exist in France where stakeholders, local initiatives, public institutions, or farmers, want to increase the number and cover of landscape elements on farms or in landscapes to increase the diversity of habitats, species, and heterogeneity of landscapes. One example is the biodiversity enhancing project in a vineyard dominated landscape of Saumur-Champigny, western France. This initiative was started in 2004 by the winegrowers' association of Saumur-Champigny (Sigwalt et al. 2012). The main objectives were to increase biodiversity, improve pest control, use fewer chemicals, and improve the commercial image of their wine. Since 2005 winegrowers have been planting hedgerows and establishing grass as cover crop between rows and in field borders. By 2010, 23km of hedgerows had been planted by 61 farmers (i.e., half of the association members). Besides the effect of having more biodiversity in the vineyard landscape, it was also found that winegrowers now pay more attention to the environment. There is a lower use of herbicides compared to before and to other farmers in the region, but only a slightly lower use of pesticides (Sigwalt et al. 2012).

In many regions in France, incentives have been provided for several years to plant hedgerows in agricultural landscapes to protect against wind and water erosion, for the conservation of biodiversity, to establish ecological corridors, favour conservation biological control, and for aesthetical landscape purposes (e.g. Chambre d'Agriculture Mayenne 2013, Conseil Général Calvados 2013, Conseil Général de l'Orne 2013, Pays de Dols de Bretagne 2013). Some examples of what type of landscape elements farmers installed on their farm and the reasons why are given in Fricotte and Vinson (2010) and Chambre Régionale d'Agriculture du Centre (2013). In other countries in Europe such financial incentives are also provided to plant hedgerows, e.g. in Germany (Bayerisches Staatsministerium für Landwirtschaft und Forsten 2007, Landschaftspflegeverband Neumarkt 2013).

In addition to preserving or increasing semi-natural landscape elements in agricultural landscapes, some farmers also install "insect hotels" near their fields (Figure 39). The different constructions provide reproduction and hibernation sites for beneficial insects and are expected to improve overall biological control of pests.

Figure 39. An "insect hotel" built by vegetable farmers in south-eastern France. The different constructions provide reproduction and hibernation sites for beneficial insects near vegetable fields in addition to semi-natural landscape elements which are also preserved. It is expected that overall biological control of pests is improved (Photo A. Wezel).

4 Conclusions and outlook

Agricultural production should provide sufficient food for the world's population while being economically beneficial for farmers, environmentally friendly, and socially acceptable. In addition, the basic food commodities should also be available at affordable prices for low-income people without impairing the quality. The foundations of this agriculture are the different practices farmers apply for crop and livestock production. Some of these practices can be considered as agroecological practices if they valorise in the best way possible ecological processes and ecosystem services by integrating them as fundamental elements in the development of agricultural practices, and not simply relying on synthetic inputs such as chemical fertiliser and synthetic pesticide application, or technological solutions such as genetically modified organisms.

Many agroecological practices already exist around the world, and are applied to different degrees in different regions and under various climatic conditions. In this publication we presented agroecological cropping and livestock practices from western Europe, in particular from France. Most of these practices include higher diversity either i) at the field level by mixing cultivars, using crop associations, and diversified crop rotations, ii) at the farm level by increasing diversity of productions, and integrating biodiversity via semi-natural landscape elements, and iii) at the landscape level by integrating natural and semi-natural rangelands into mixed crop-livestock systems, or by integrating a broad range of landscape elements to improve biological control, pollination, and erosion control. However, integrating higher diversity also implies, for farmers, managing more complex systems, and in many cases also taking higher economic and technological risks.

Applying some of the agroecological practices presented here might already have some positive effects, but what is more challenging is not to apply single practices, but to develop a systems approach where these agroecological practices are used to support environmental, but also economic and social sustainability. Therefore, the use of multiple practices is needed for optimum management of agroecosystems, but it must be feasible for such practices to be implemented by farmers, and they should be adapted to local farming conditions.

The uptake into today's agriculture of most of the agroecological practices presented here on farm and landscape levels has so far been low, and the outlook for a broader implementation over the next decade remains at a low or medium potential. In contrast, biological pest control, reduced tillage, organic fertilisation, drip irrigation, split fertilisation, and cultivar choice already have medium or high integration levels in today's agriculture, and medium or high potential for the future. Nevertheless, new and broader implementation of agroecological practices will depend on research incentives and policies which would support some of these practices.

Thus far there has been no clear EU strategy for agroecological practices and sustainable agriculture, and national action plans and political will on this topic still remain marginal. France is the sole country among the 28 Member States to have set up an explicit "Agroecological project for France" strategy in December 2012. However, the newly defined Common Agricultural Policy (CAP) for 2014-2020 includes further elements, in addition to already existing agri-environment measures, which are oriented towards some agroecological practices.

The major novelty of the new CAP is a new financial sub-heading named "Green payment" representing 30 % of direct aids. A green component based on compulsory practices to be followed by farmers addressing both climate and environment policy goals is set up in Pillar 1 (direct payments) while so far the trend was only to reinforce environmental measures within Pillar 2 (rural development). Greening practices take the form of simple, generalised, non-contractual and annual actions that go beyond the common requirements and the regulatory cross-compliance which is the EU directive for good agricultural and environmental practices. The three proposed compulsory practices of greening are (Council of the European Union 2013a) :

- crop diversification with a minimum of two different crops for between 10 and 30 ha of arable land and three different crops for beyond 30 ha of arable land;
- maintenance of permanent grasslands in and outside environmentally sensitive areas, including permanent grasslands on carbon rich soils;
- establishment or maintenance of ecological focus areas for holdings where arable land covers more than 15 hectares corresponding to at least 5 % of the arable land of the holding (and planned to be increased to 7 % from 2017 onwards). Ecological focus areas may include fallow land, terraces, landscape features, buffer strips, afforested areas, hectares of agroforestry, strips of eligible hectares along forest edges, but also areas with short rotation coppice where no use is made of mineral fertiliser and/or plant protection products, areas with catch crops and green cover, and areas with nitrogen-fixing crops.

In reality those practices are not a novelty for some member states, being more or less already included in the cross-compliance in one way or another. Furthermore, the CAP reform established in spring 2014 allows Member States to apply for exemptions and equivalences with current farming practices. In that respect the impact of greening might be much lower than expected at the beginning.

To conclude, many agroecological practices exist already around the world and are applied to different degrees in different world regions, illustrated here with examples from France and Europe. What many of them have in common is that they include, depending on the practice, higher diversity either at the field, farm, or landscape scale. However some agroecological practices have so far a low level of integration in today's agriculture, and their potential to be more broadly implemented in the next decade will also depend strongly on policies and incentives provided to support not only some, but the whole set of agroecological practices. There are encouraging signs from policymakers, but today a broad strategy, widely accepted by the large diversity of stakeholders, is still missing.

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