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REVIEW ARTICLE

Agroecological practices for sustainable agriculture. A review

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Abstract The forecasted 9.1 billion population in 2050 will require an increase in food production for an additional two billion people. There is thus an active debate on new farming practices that could produce more food in a sustainable way. Here, we list agroecological cropping practices in temperate areas. We classify practices according to efficiency, substitution, and redesign. We analyse their advantages and drawbacks with emphasis on diversification. We evaluate the potential use of the practices for future agriculture. Our major findings are: (1) we distinguish 15 categories of agroecological practices (7 practices involve increasing efficiency or substitution, and 8 practices need a redesign often based on diversification). (2) The following agroecological practices are so far poorly integrated in actual agriculture: biofertilisers; natural pesticides; crop choice and rotations; intercropping and relay intercropping; agroforestry with timber, fruit, or nut trees; allelopathic plants; direct seeding into living cover crops or mulch; and integration of semi-natural landscape elements at field and farm or their management at landscape scale. These agroecological practices have only a moderate potential to be broadly implemented in the next decade. (3) By contrast, the following practices are already well integrated: organic fertilisation, split fertilisation, reduced tillage, drip irrigation, biological pest control, and cultivar choice.

Keywords Agroecology · Diversification of cropping system · Efficiency increase · Substitution · Systems redesign

Contents

1 Introduction

The forecasted increase in world population of up to 9.1 billion in 2050 (United Nations 2009) will require a major effort to increase food production for an additional two billion

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people compared to today. Disregarding allocation problems, overproduction and food waste in some world regions, this would mean that about 30 % more food is needed at the global level. Thus, world agriculture is facing major challenges in producing this additional food. In addition, there has been an increasing demand in the last decades to not only produce larger quantities, but to also achieve development towards sustainable agriculture where production is simultaneously environmental friendly, socially fair, and economically beneficial. It will be necessary to develop agricultural food production practices for all types of agriculture, be it conventional, integrated, or organic agriculture.

There is a strongly contrasting, on-going debate around the most appropriate agricultural production practices with which to reach the goal of higher, and also sustainable food production (e.g. Borlaug 2000; Huang et al. 2002; McNeely and Scherr 2003; Médiène et al. 2011; Perfecto and Vandermeer 2010; Phipps and Park 2002; Prasifka et al. 2009; Swaminathan 2007; Tilman et al. 2002). Agricultural options range from high technology-based practices to ecology-based practices. On the one hand, precision farming (Srinivasan 2006) or use of genetically modified crops (e.g. Huang et al. 2002; Phipps and Park 2002) could help match the future food demand. On the other hand, practices such as natural biological control of pests (Fig. 1), such as integrating natural landscape elements into agricultural landscapes (Fig. 2) in order to decrease pesticide use (e.g. Altieri and Nicholls 2004; Gurr et al. 2004) or no or reduced tillage, that increase soil biota activity and improve soil fertility (Holland 2004), are other possible options.

Fig. 1 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 life cycle of beneficial insects which then can control pests. The present photo shows a ladybird beetles, a natural predator of aphids, on organic wheat in southeastern France (photo by A. Wezel)

Fig. 2 Landscape elements surrounding a cereal field, southeastern France. Woody landscape elements for example 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 by A. Wezel)

Practices such as organic crop fertilisation, crop rotations, or biological pest control are well-known agricultural practices that have been widely used for a long time. However, during the last two decades, they 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 are already mentioned in literature, e.g. cover crops, green manure, intercropping, agroforestry, biological control, resource and biodiversity conservation practices, or livestock integration (Altieri 1995, 2002; Arrignon 1987; Gliessman 1997; Wojtkowski 2006). Nevertheless, we are still lacking to specify the characteristics that identify them as agroecological practices. What are their advantages and constraints, and which potential do they have in the future? For example, agroforestry in developing countries, with the integration of trees into cropland, is not beneficial per se when crop yields are strongly decreasing due to loss of cropland or competition for light, nutrients, and water with trees, therefore generating a risk for smallholder family survival. Moreover, what are the more recently developed practices that could be promising in developing a more sustainable agricultural production, and could be considered as innovative agroecological practices? An innovative practice can be something completely new, but also a practice based on age-old principles or techniques that have been little studied (Uphoff 2002) and which are newly adapted, thus creating a novelty for improvement. The origins of innovative practices can be quite different. They may be something new (discovered accidentally), something purposefully sought through experimentation (such as different potential practices), or they may be the outcome of a radical change in thinking, or approach, to establish a new system (e.g. biodynamic agriculture), thus creating innovations for the practical implementation of the new system.

The aim of this review is to define agroecological practices and present them with their constraints, advantages and their potential in a concise manner. So far, agroecological practices have been presented in books or papers, some with extensive literature, but either only focusing on one practice or on only some of them, and in most cases only generally calling them agroecological practices without defining what qualifies them as such. Also, a summarised evaluation of the potential of a large set of agroecological practices has, to our knowledge, not yet be made in a review paper. A final point is that evaluating agroecological practices has been to a larger extent done for practices which are mainly used in the tropics and subtropics, but so far this has only been done to a limited extent focusing on temperate areas.

Therefore, in this paper, we define and present agroecological cropping practices of crop-based farming systems in temperate areas in analysing their potential and constraints, and in classifying them into efficiency increase, substitution, and redesign practices. We also analyse which practices are based on diversification of systems. In addition, we carry out a detailed analysis of more recently developed agroecological practices by evaluating their potential and constraints to contribute to the different goals of sustainable agriculture: to provide sufficient food for a growing world population not to be at the detriment or risk to the environment and to assure economic viability for farmers.

2 Definition of agroecological cropping practices and analytical framework

In our understanding, agroecological practices are agricultural practices aiming to produce significant amounts of food, which valorise in the best way ecological processes and ecosystem services in integrating them as fundamental elements in the development of the practices, and not simply relying on ordinary techniques, such as chemical fertiliser and synthetic pesticide application or technological solutions, such as genetically modified organisms. Indeed, agroecological practices contribute to improving the sustainability of agroecosystems while being based on various ecological processes and ecosystem services such as nutrient cycling, biological N fixation, natural regulation of pests, soil and water conservation, biodiversity conservation, and carbon sequestration. Some of these practices have already been applied in varying degrees in different regions of the world for years or decades, while others were more recently developed and still have a limited rate of application.

In this review, we present agroecological practices in temperate areas, and classify them according to the analytical framework of Hill and MacRae (1995). It describes an agricultural transition towards sustainable agriculture by defining three (usually) consecutive stages: efficiency increase, substitution, and redesign. Nevertheless, some farmers enter the third stage directly when dramatically changing their cropping systems, e.g. moving to no tillage systems or agroforestry systems.

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. Note that one practice could correspond to one or more categories of such a framework (Table 1).

Furthermore, we distinguish between practices that are either related to crop management or the management of landscape elements. In the case of crop management practices, we distinguish different types: (1) practices addressing crop choice, crop spatial distribution, and crop temporal successions; (2) tillage practices; (3) fertilisation practices; (4) irrigation practices; and (5) weed, pest, and disease management practices. In the case of landscape element management, we distinguish between practices at the field/farm level and landscape level. In Fig. 3, we summarise the categories of practices and show their scales of application.

In developing agroecological practices, the question of diversification is inevitable, as these practices are based on ecological processes and provision of ecosystem services. In the last decade, a growing number of scientists have claimed that species diversity has to be (re)integrated into cropping systems for a host of reasons, e.g. higher agroecosystem resilience to perturbation (Jackson et al. 2007; Loreau 2000; Malézieux et al. 2009; Tilman et al. 2006; Vandermeer et al. 1998, 2002), decreased pest outbreaks (including weeds), or biodiversity conservation (e.g. Médiène et al. 2011). Diversification refers to integration of more diverse cultivars, crops or intercrops into the cropping systems, or valorising natural biodiversity for agricultural purposes such as conservation biological control. Thus, we also specify in Table 1 if the presented practices lead to system diversification.

3 Efficiency increase and substitution agroecological 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.

Table 1 Agroecological crop and landscape element management practices. Each practice is briefly described and assessed according to the conceptual framework (efficiency increase, substitution, redesign (ESR)). In case of diversification practice, a D is inserted in the D column

Type of management	Definition—principles	ESR	Advantages and constraints	D	References
Efficiency increase and substitution practices					
Crop choice, crop spatial distribution, and crop temporal successions					
Cultivar choice	Use of resistant crops to biotic and abiotic stresses (and mixing them) or crops with selected traits that enhance rhizosphere activities (e.g. mycorrhiza, plant growth-promoting rhizobacteria).	E, S	Advantages: Increase and/or stabilization of yields, pest control, and resistance to water stress. Reduction of fertiliser or pesticide use. Constraints: availability and costs of new and adapted varieties.		Tilman et al. (2002); Ryan et al. (2009)
Crop fertilisation					
Split fertilisation	Fertiliser application (chemical and organic) with several operations	E	Advantages: reduction of fertiliser use. Increased uptake efficiency by crops. Reduction of risk of ground and surface water contamination. Constraints: increase in labour and energy demand due to increase in fertiliser applications. Knowledge/estimation of crop N demand.		Fageria and Baligar (2005); Zebarth et al. (2009)
Biofertiliser	Application of living microorganisms to seed, plant surfaces, or soil	E, S	Advantages: reduction of fertiliser use. Improvement of nutrient availability. Constraints: low scientific knowledge. Variable and inconsistent effects. Low commercialization rate.		Vessey (2003); Malusá et al. (2012)
Organic fertilisation	Application of exclusively organic or mixed with inorganic fertilisation	E, S, R	Advantages: reduction of chemical fertiliser use. Reduction of energy consumption for transport when using on-farm manure or from nearby cooperating farms. Reduction of risk of ground and surface water contamination. Enhancement of soil biological activity. Constraints: increase in difficulties to optimise N availability for crops with organic fertiliser application. Costs for organic fertiliser or manure/compost and transport if not available on the farm.		Sanchez et al. (2004); Birkhofer et al. (2008); Steenwerth and Belina (2008)
Crop irrigation					
Drip irrigation	Use of drip irrigation (without or in combination with cover crops or mulch).	E	Advantages: Increase of water use efficiency and reduction of water use. Less risk of salinization of soils. Reduction of evaporation with cover crops or mulch. Constraints: increase in investment, equipment, and management costs.		Lopes et al. (2011)
Weed, pest and disease management					
Natural pesticides/ Botanical pesticides	Pesticides derived from plants or plant extracts	S	Advantages: decrease or absence of water or product contamination from synthetic pesticides. Decrease in risk for human health. Usable in organic agriculture.		Coulibaly et al. (2002); Charleston et al. (2005); Sinzogan et al. (2006); Isman (2006, 2008); Regnault-Roger and Philogène (2008)

Table 1 (continued)

Type of management	Definition—principles	ESR	Advantages and constraints	D	References
			Constraints: variable efficiency to control pests. Restricted availability. Low scientific knowledge. National regulations and registrations. Costs.		
Biological pest control	Control of weeds, pests, and diseases based on introduction of natural enemies, pheromones	S	Advantages: reduction of soil and water contamination from pesticides. Reduction of risk for human health. Constraints: variable efficiency depending on pests. Knowledge and management intensive. Costs.		Hokkanen (1991); Gurr and Wratten (2000); Altieri and Nicholls (2004); Khan and Pickett (2004)
Redesign practices					
Crop choice, crop spatial distribution, and crop temporal succession					
Crop choice and rotations	Integration of different crops in rotations (including cover crops)	S, R	Advantages: reduction of weed and pest infestation and thus reduced use of pesticides. Reduction of fertiliser use if leguminous crops are used. Increase in soil biological activity. Reduction of leaching and erosion with cover crops. Increase in diversity of feed and food produced. Constraints: management of a larger number of crops (labour, knowledge, technical equipment, market access). Risk of pest development with cover crops (e.g. snails). Difficulties in destroying cover crops.	D	Altieri (2000); Bàrberi (2002); Deike et al. (2008); Scholberg et al. (2010)
Intercropping and relay intercropping	Intercropping: coexistence of two or more crops on the same field at the same time. Relay intercropping : undersowing of relay crops in already existing crop (e.g. undersowing of legumes in cereals)	E, S, R	Advantages: increase in land productivity. Reduction of pest and disease impact. Improvement of nitrogen content of soils in case of intercropping of legumes. Reduction of inputs. Improved soil structure and fertility. In case of relay intercropping: mitigation of competition risk for main crop and facilitation of N nutrition for undersown crops. Constraints: increase in labour demand for harvesting and association management. Lack of technical equipment for harvesting. Risk of inter-species competition. Pest facilitation (e.g. slug). Increase of complexity of system management.	D	Malézieux et al. (2009)
Agroforestry with timber, fruit or nut trees	Alley intercropping with crops and rows of woody vegetation. Scattered fruit trees in meadows.	E, S, R	Advantages: increase in land productivity. Decrease in nutrient leaching and soil erosion. Diversity of production: wood (timber, firewood) or fruit trees and crops. Provision of mulch material. Protection of crops from intense solar radiation and wind. Increase in animal and plant species diversity in fruit tree meadows. Constraints: loss of cropped area in case of wood production. Adequate management of woody rows. Risk of competition between crops and woody vegetation. Increase in labour demand.	D	Buck et al. (1998); Rigueiro-Rodrígues et al. (2009)

Table 1 (continued)

Type of management	Definition—principles	ESR	Advantages and constraints	D	References
Weed, pest and disease management					
Allelopathic plants	Integration of allelopathic plants in crop rotation (including as intercrops or cover crop). Trap crops or push-pull strategies.	S, R	Advantages: reduction of weed or pest pressure without use of pesticides. Reduction of soilborne pests and diseases with biofumigation. Constraints: results depend on local conditions. Control of allelopathic plants. Lack of scientific knowledge.		Hokkanen (1991); De Albuquerque et al. (2011); Shelton and Badenes-Perez (2006); Médiène et al. (2011); Ratnadass et al. (2012)
Tillage management					
Direct seeding into living cover crops or mulch	Planting of crops directly (no tillage) in preceeding cover crop (living or destroyed, i.e. mulched) or crop residues.	E, S, R	Advantages: reduction of energy consumption for seedbed preparation. Decrease in wind and water erosion. Reduction of soil compaction. Increase in soil biota activity. Increase in soil organic matter and carbon sequestration. Limitation of weed growth, reduction of herbicide use. Constraints: difficulty to efficiently control weeds, living mulch and cover crops. Increase in energy consumption with mechanical weed control. Yield reduction due to competition between crops and cover crops/living mulch. Risk of environmental impact when high amounts of herbicides are applied for weed control.		Soane et al. (2012);Holland (2004)
Reduced tillage	Use of only superficial tillage without soil inversion.	E, S, R	Advantages: reduction of energy consumption. Decrease in wind and water erosion. Reduction of soil compaction. Increase in soil biota activity. Increase in soil organic matter and carbon sequestration. Constraints: difficulty to efficiently control weeds. Risk of environmental impact when high amounts of herbicides are applied for weed control.		Soane et al. (2012); Holland (2004)
Management of landscape elements					
Integration of semi-natural landscape elements at field or farm scale	Planting and management of vegetation strips and hedges in fields and at field borders.	S, R	Advantages: increase in natural control of pests (habitat creation). Biodiversity conservation. Improvement of pollination of crops. Reduction of pesticide use. Protection against surface water contamination. Wind and soil erosion protection. Constraints: risk of creating habitats for pest species. Loss of crop area. Need for management of landscape elements. Efficiency of pest control.	D	Thies and Tscharntke (1999); Östman et al. (2001); Altieri and Nicholls (2004); Tscharntke et al. (2007); Gardiner et al. (2009); Obrycki et al. (2009)
Planting or managing landscape elements	Management of hedges, vegetation strips and other landscape elements at territory scale.	R	Advantages: reduction of pest pressure. Increase in natural enemy densities, reduction of pesticide use. Reduction of contamination of surface water. Increase in wind and soil erosion protection.	D	Östman et al. (2001); Baudry and Jouin (2003); Thies et al. (2003); Altieri and Nicholls (2004); Gardiner et al. (2009); Wu et al. (2010)

Table 1 (continued)

Type of management	Definition—principles	ESR	Advantages and constraints	D	References
			Enhancement of biodiversity conservation. Use of woody biomass as energy source. Constraints: risk of creating habitats for pest species. Loss of crop area. Need for management of landscape elements. Efficiency of natural pest control. Requirement of multi-stakeholder approach in combination with landscape management.		

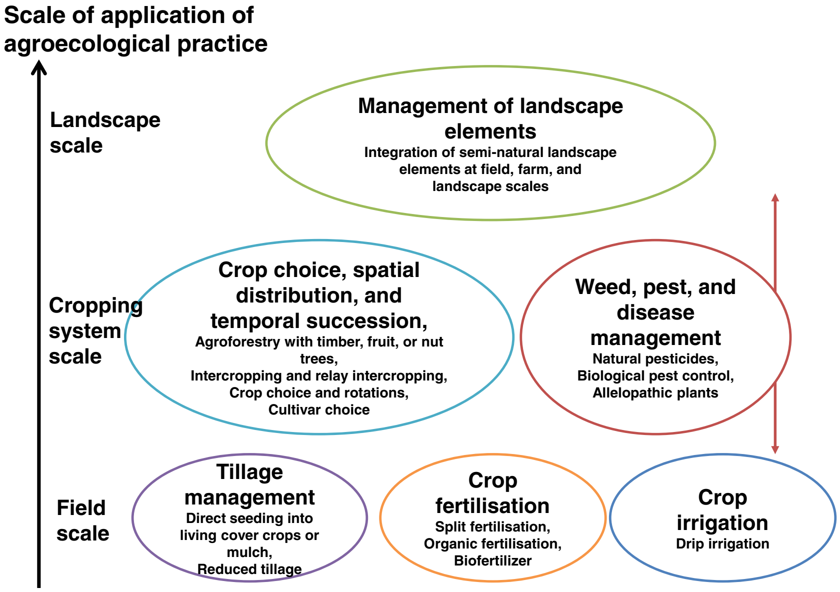
3.1 Crop choice, crop spatial distribution, and crop temporal successions

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). Plant breeding (hybrid and conventional breeding) is thus an option for developing agroecological practices, considering both cost and availability to farmers as important constraints (Table 1). Moreover, crop resistance to a pathogen is likely to be transitory resistance, as new pathogens are concomitantly developing since crop resistance acts as a selective agent on pathogen populations (Tilman et al. 2002). Nevertheless, combining crop resistance to spatial or temporal crop diversity (rotation and spatial allocation) is a good opportunity for reducing this risk.

Another important point is to choose crop species or cultivars which favour the development of beneficial soil microorganisms. These beneficial microorganisms are mainly located in the soil rhizosphere and stimulate plant growth by different mechanisms (enhanced nutrient acquisition, protection against pathogens, and modulation of phytohormone synthesis). Arbuscular mycorrhizal fungi (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). Crop choice and crop rotation are important factors to consider in order to favour their development. The diversification of crop rotations and the reduction of non-mycorrhizal crops (e.g. rapeseed) could enhance arbuscular mycorrhizal fungi populations and diversity. Gianinazzi et al. (2010) also highlight the importance of changing breeding strategies from a selection of plants adapted to high fertilisers and biocide usage, to a selection of plants adapted to AMF attributes. 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 (Hartmann et al. 2009). Breeding strategies and biotechnology, through the manipulation of root exudates, have the potential to improve plant nutrition and protect plants from stresses, but improvement of nutrient availability has yet to be determined (Ryan et al. 2009).

In general, crop or cultivar choices help to improve the efficiency of cropping systems, reduce pesticide use, and can be implemented in a substitution stage. Resource use efficiency can be improved by planting or sowing a crop with lower needs after a nutrient or water demanding crop. Improving

Fig. 3 Different categories of agroecological practices identified in the review. Their scale of application ranges from field scale to landscape scale. Most practices are either applied at the field or cropping system scale. The arrow with weed, pest, and disease management practices indicates that they are also applied on the field scale and landscape level



water use efficiency in water-scarce conditions (particularly rainfed water) is possible with relevant crop rotations (Pala et al. 2007; Salado-Navarro and Sinclair 2009; Turner 2004). Moreover, in conditions where rainfall events are sporadic and sometimes violent (storms in the Mediterranean climate, for example), cover crops can play an important role by reducing surface runoff and permitting a better water infiltration, possibly gainful for the next crop (Celette et al. 2008; Gaudin et al. 2010).

3.2 Crop fertilisation management

Splitting N fertiliser application is an effective means of improving N use efficiency in agricultural crop production (Table 1). The objective is to match the supply of N to the crop N demand in time (Fageria and Baligar 2005; Zebarth et al. 2009). The timing of applications could be triggered depending on the actual N uptake of the crop, which can be measured or estimated with the use of different tools (Lemaire et al. 2008). This improved matching of supply and demand would help to improve the efficiency of the practice and to limit ground and surface water contamination by fertilisers. However, it requires increased labour; the estimation of crop N demand might be difficult.

Utilisation of biofertilisers is another way to reduce fertiliser inputs and improve nutrient availability. They are "substances which contain living microorganisms which, when applied to seed, plant surfaces, or soil, colonise the rhizosphere or the interior of the plant, and promote growth by increasing the supply or availability of primary nutrients to the host plant" (Vessey 2003). Three major groups of microorganisms are considered biofertilisers: AMF, PGPR, and nitrogen fixing rhizobia (Malusá et al. 2012). The latter is used with legumes and has existed for over a century. Commercialization of PGPR and AMF inoculants remains low besides the utilisation of an *Azospirillum* inoculant, which is available for a variety of crops in Europe and Africa (Vessey 2003). Some experiments have reported plant growth promotion, increased yield, and uptake of N and some other elements through PGPR inoculation (Singh et al. 2011) or AMF inoculation (Ortas 2012; Pellegrino et al. 2011). Biofertilisers can decrease the use of synthetic fertilisers and reduce environmental pollution to a considerable extent. But this technology 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). Indeed, the effect of biofertilisers on plant growth has been frequently hampered due to the variability and inconsistency of results between laboratory, greenhouse, and field studies.

Organic fertilisation is a way of substituting inorganic fertilisers and of improving the efficiency of fertilisation by improving general soil fertility. However, it can also lead to a necessary redesign of the system. Application of organic fertiliser causes enhanced soil biological activity (Birkhofer et al. 2008; Steenwerth and Belina 2008) and potentially increased soil mineralisation. Nevertheless, the constraints of these practices may include higher labour and energy demands, and difficulty in optimising N availability in soils with organic fertilisation as well as in matching 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. Finally, the introduction of more organic fertilisers into the cropping system may entail introducing livestock into the farm. This would imply a redesign of the whole farming system.

3.3 Crop irrigation

Drip irrigation, especially in horticultural systems, offers a high potential to limit water inputs, to improve water use efficiency, and to better match the crop water demand in time and space (Table 1). It also limits the risk of soil salinization. The major constraints 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.

3.4 Weed, pest, and disease management

The use of natural pesticides is an agroecological practice that replaces synthetic pesticide use (Table 1). Natural pesticides, often also called botanical pesticides or botanicals, have a high potential as an alternative to synthetic pesticides and their associated negative effects. Nevertheless, still not much is known about them, particularly regarding larger-scale applications in agriculture. Some of them may also cause environmental pollution. Only a few natural pesticides are presently commercially used due to constraints of variable efficiency of pest control, availability, national regulations and registration, and costs (Isman 2008). Among botanical pesticides are, for example, pesticides which are (1) derived from the seeds of the trees, (2) based on plant essential oils, (3) based on pyrethrum extracted from flowers, (4) derived from crude aqueous extracts of plants, and (5) based on extracts of trees (Batish et al. 2008; Charleston et al. 2005; Coulibaly et al. 2002; Isman 2006, 2008; Mordue and Nisbet 2000; Regnault-Roger and Philogène 2008; Sinzogan et al. 2006). 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 them are derived from tropical or subtropical plants that grow naturally in such countries (Isman 2006, 2008; Regnault-Roger and Philogène 2008).

In addition to botanical pesticides, the so-called biopesticides are also used. This includes the application of bacteria, AMF inoculants, or other fungi that can control deleterious organisms (Vessey 2003; Whipps 2001). Biopesticides impact pests by antibiosis, competition, induction of plant resistance mechanisms, inactivation of pathogen germination, and/or degradation of the pathogenicity of the pathogens (Whipps 2001). Nevertheless, field application often fails to counteract pathogen development due to insufficient rhizo- and/or endosphere colonisation (Compant et al. 2010; Verbruggen et al. 2013).

Biological pest control includes different agroecological practices that reduce or replace pesticide use (Table 1). Biological pest control is based on the substitution of chemical pesticides by releasing natural enemies into the agroecosystems. Using pheromones to disturb sexual reproduction of targeted insect pests is another biological control option.

Natural pesticides and biological pest control reduce the risk of water pollution and risks to human health (e.g. Altieri and Nicholls 2004; Gurr and Wratten 2000). They might be difficult to apply as their efficiency and availability depends on the pest, because they involve increased management and costs and require knowledge.

To summarise, we defined seven categories of agroecological practices that rely either on increasing efficiency by reducing input consumption and increase crop productivity, or on substitution practices that substitute an input or a practice. These agroecological practices are: crop choice, splitting fertilisation, biofertilisers, organic fertilisation, drip irrigation, biological pest control, and natural pesticides.

4 Redesign agroecological practices

Redesign practices signifies that the whole, or at least a large part, of the cropping system should be rethought with the adoption of the practice in question. This redesign is often carried out together with a diversification of systems in increasing the diversity of cultivars, crops in the rotation, or in valorising natural biodiversity for conservation biological control.

4.1 Crop choice, crop spatial distribution, and crop temporal succession

4.1.1 Cover crop/green manure

Use of cover crops is a widely applied agroecological practice to limit fertiliser inputs and reduce risk of water contamination due to a decreased risk of leaching (Sanchez et al. 2004; Scholberg et al. 2010), and also to reduce soil or wind erosion. Integration of cover crops into the rotation automatically incurs crop diversification (Table 1). Soil biological activity is also enhanced, and in the case of use of legumes, there is provision of N supply for the next crop (Birkhofer et al. 2008; Steenwerth and Belina 2008). Leguminous plants can be an important source of easily absorbable nitrogen for other crops in the rotation due to their ability to fix atmospheric nitrogen (Fustec et al. 2010). They 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. Certain species can also be incorporated into the crop rotation in order to 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).

4.1.2 Crop temporal successions

Crop rotation is a more classic way to introduce crop diversity into an agroecosystem. It consists in managing the crop succession to optimise positive interactions and synergies between crops. As crop presence during the rotation is normally sequential, interactions between species are mostly indirect, and also depend on crop management and growth conditions. In general, crop rotation affects soil fertility, therefore influencing plant production as well as the prevalence of pests and diseases (Altieri 1995).

First, cropping sequences can be optimised to improve nutrient availability and to limit fertiliser need. For example, integration of leguminous plants into the rotation allows fixing atmospheric nitrogen, and provides an important source of easily absorbable nitrogen for subsequent crops. Second, certain crop rotations favour soil protection and conservation by increasing soil cover, e.g. with the introduction of cover crops or favouring winter crops, but also by improving carbon content and soil fertility which permits an increase in soil stability (Dogliotti et al. 2004; Watson et al. 2002). Root systems of the subsequent crop play an important role as their roots (as crop residues) stimulate soil biological activity and improve soil structural stability. Up to 40 % of the microbial carbon uptake comes from root systems, e.g. exudates or root turnover (Richardson et al. 2009). In this sense, introduction of cover crops and catch crops into the rotation is a potentially good option (Bilbro 1991; Bruce et al. 1991; Nearing et al. 2005; Wu et al. 2010). Additionally, as mentioned before, they can mitigate nitrate leaching and improve nutrient use efficiency. Under temperate conditions, they are also likely to improve water infiltration during the winter period and to increase water availability for the following crops (Celette et al. 2008; Justes et al. 2002).

Third, crop rotations can also be an efficient way to reduce pest and disease prevalence by diversifying crops in the cropping sequence while avoiding the presence of successive host crops for diseases (Colbach et al. 1997a, b). In addition, crop management, e.g. crop residues and fertilisation, play an important role. Fourth, crop rotation is known to be an efficient way to reduce weed infestation. This is due to the specific ability of some crops to rapidly cover the soil, thus competing with weeds for soil and light resources. In addition, crop management is important for weed control with different possible weeding interventions at different moments during the year (Anderson 2007; Bàrberi 2002; Koocheki et al. 2009).

Optimising ecological services cannot be the only approach to better manage crop rotations. An important point for redesigning the crop rotation system is to maintain good farm productivity and profitability. This consists, then, in optimally allocating resources, e.g. land, time, energy, fertilisers, and water, to improve profitability, productivity, and ecological services (Dogliotti et al. 2003; Dury et al. 2011).

4.1.3 Crop spatial distribution—intercropping and agroforestry

Intercropping may be defined as the coexistence of two or more crops in the same field at the same time (Table 1). 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. 2009). Interactions can be positive (facilitation) or negative (competition). The simplest differentiated crop mixtures (or mixed intercropping) are row and strip intercropping where at least one of the associated crops is planted in a row (or strip). These arrangements consist of "full intercropping", where interactions between associated species occur throughout the crop cycle. This differs with relay intercropping, where two or more crops are grown together only for part of their life cycles, thus limiting interactions between species (Vandermeer 1989). Other categories sometimes mentioned are associations partially composed of perennial species (e.g. agroforestry—see below).

The intercropping systems are assumed to have potential advantages in productivity, stability of outputs, resilience to disturbance, and ecological sustainability, though they are generally considered harder to manage (Vandermeer 1989; Fig. 4). The main issue in such a system is managing competition for resources between the associated crops (Ong 1995; Ozier-Lafontaine et al. 1998; Van Noordwijk et al. 1996;

Fig. 4 Relay intercropping of wheat and undersown clover in southeastern France. In relay intercropping, leguminous species are often sown some weeks after the crop to reduce the risk of competition between crops. They assure a supplementary soil cover in particular after crop harvest. There, they limit nutrient leaching, wind, and water erosion, fix Nitrogen, and can potentially be harvested as forage (photo by F. Boissinot)

Willey 1990). The first interest of intercropping is to improve land productivity by favouring complementarity of associated crops. Intercropping generally permits improvement of resource use efficiency, notably radiation use (Bedoussac and Justes 2010; Ozier-Lafontaine et al. 1997; Sinoquet and Caldwell 1995). In some situations, increased resource use efficiency is the consequence of a facilitation process (e.g. association with legume species; Jensen et al. 2010; Köpke and Nemecek 2009; Schmidtke et al. 2004). Root exudates of some legume species can improve soil phosphorus availability (Ae et al. 1990), solubilizing soil organic phosphorus, but also improve organic fertilisation (Li et al. 2005; Midmore 1993). Other types of facilitation may be observed when one of the associated crops offers a service to the other. For example, when wheat was associated with a clover grass, twice as much earthworms were observed in the soil than with a sole crop (Schmidt et al. 2003). As another example, cereal crops can help pea crops mitigate weed infestation due to their better competitivity and higher resource use efficiency in an intercropped system than as a sole pea crop (Hauggaard-Nielsen et al. 2001, 2006). Intercropping also improves soil physical structure and soil fertility. Compaction and penetration resistance are lower in such systems, and there is an improvement in structural stability (Carof et al. 2007; Latif et al. 1992). Moreover, soil cover is generally increased with intercropping, mitigating both soil crusting and erosion (Le Bissonnais et al. 2004).

Different types of agroforestry practices can be also considered agroecological practices since they reduce nutrient leaching, conserve soils, increase diversity of the production system, and produce complementary wood for various uses (e.g. Buck et al. 1998; Rigueiro-Rodrígues et al. 2009). In Europe, there are different agroforestry systems that integrate crops and, more generally, woody plants (Rigueiro-Rodrígues et al. 2009; Fig. 5). However, there are also more specialised systems that include fruit or nut tree integration. In some cases, these fruit or nut tree systems are coupled with extensive grazing of meadows below or between the trees. In general, constraints for intercropping and agroforestry systems are higher management needs, loss of cropped land for the main crop, and often a higher labour demand.

4.2 Weed, pest, and disease management—allelopathic plants

Some plant species have the ability to produce chemical compounds which negatively influence the growth and development of weeds, pests, or diseases (De Albuquerque et al. 2011; Kruidhof et al. 2008; Tabaglio et al. 2008; Weston 1996). Therefore, the introduction of so-called allelopathic plants into crop rotations is a promising agroecological practice intending to reduce pesticide use while providing good crop yields. 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 crops such as rye, sorghum, or sunflower can be used as green manure or cover crops due to their direct allelopathic effects: inhibition of weed seed germination and/or development due to the release of root exudates (De Albuquerque et al. 2011). An onion crop may be regarded as a “push” crop 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). In comparison, Brassicaceous crops primarily act indirectly on weeds, pests, and diseases through the decomposition of their residues in the soil (Médiène et al. 2011; Ratnadass et al. 2012). This delayed allelopathic effect, called biofumigation, has the ability to reduce soil-borne pests and diseases such as fungi (Médiène et al. 2011), bacteria, and nematodes (Ratnadass et al. 2012).

Fig. 5 Olive tree agroforestry system with undergrowth of leguminous species and grassland in Sardinia, Italy. This type of agroforestry system allows combining different crops on the same field. Resource use efficiency is increased because of different root systems, better nutrient cycling can be expected, legumes fix nitrogen, and below tree species cover the soil and wind and water erosion (photo by M. Casagrande)

Allelopathic effects are not only negative for organisms. Their positive effects can be used for managing 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-Perez 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).

Although there is a wide range of possibilities to benefit from allelopathic plants in temperate agroecosystems, so far, this type of practice is not widely applied. First, there is a lack of understanding of the biological processes. Second, efficiency and results are highly variable depending on local conditions (De Albuquerque et al. 2011; Médiène et al. 2011), and third and allelopathic crops can also behave as pathogen–host (Ratnadass et al. 2012).

4.3 Tillage management

Shifting from conventional to reduced tillage or no tillage (direct seeding) helps to reduce energy consumption, decreases wind and water erosion, reduces soil compaction, increases soil biota activity, increases soil organic matter, and thus carbon sequestration (Table 1).

No tillage corresponds to tillage practices without soil disturbance, such as direct seeding into a living crop or mulch (Fig. 6). Specific machinery may be used, such as direct seeders, which are comprised of coulter discs or tines for cutting and opening furrows for seeding. Reduced tillage corresponds to minimal soil disturbance without soil inversion (in contrast to ploughing). The soil is only worked to a depth of 5–15 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. Many authors have discussed advantages of these practices for improving soil fertility (El Titi 2003; Holland 2004), with a high impact on soil fertility with no tillage and with a lower impact on soil fertility with reduced tillage. Reduced or no tillage practices are currently spreading throughout the world, including temperate areas (Holland 2004; Peigné et al. 2007; Soane et al. 2012).

Reduced or no tillage practices help reduce energy inputs and thus increase cropping system efficiency. Other advantages are protecting the soil from erosion (organic matter at the soil surface), stocking organic C (less C mineralisation), and favouring soil biodiversity to promote 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 because increased numbers of predators, such as ground beetles, are found in no tillage conditions (Kromp 1999).

Fig. 6 Direct sowing of soybean into rye in southeastern France. This practice allows permanent soil cover and thus control weeds, decrease nutrient leaching, wind, and water erosion. Also soil organic matter is increase and higher soil biota activity achieved which leads to improve soil fertility (photo by J. Peigné)

Although no tillage and reduced tillage are promising practices, there are still considerable constraints for adoption. A primary one 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 result in no clear conclusion regarding their effect 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.

To alleviate constraints and increase efficiency, introduction of such practices implies redesigning the cropping systems. For instance, to better control weeds, it is necessary to rethink the cropping system as a whole, e.g. modifying the choice of crops and crop rotations.

4.4 Management of landscape elements

More recent agroecological practices and approaches are the integration, or re-integration, of natural or semi-natural landscape elements such as hedges and vegetation strips, either in or around the field (Fig. 2), or at a landscape scale. Landscape elements have good potential to provide habitats and overwintering sites as well as resources such as alternative prey for beneficial insects or other pest predators (Fig. 1), thus reducing the need for pesticide applications. Due to higher natural plant diversity and flowering, they can also positively influence crop pollination as they attract pollinators and host them outside the crop flowering period (Ricketts et al. 2008). The in-field and around-field landscape elements also protect against wind and soil erosion 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 may also harbour habitats for pest species, and that the efficiency for natural pest control may vary considerably. In addition, they reduce the cropped area and potential food production, and have to be managed by farmers.

Current research regarding the integration of landscape elements into agricultural landscapes faces the challenge of improving biological control of pests in order to reduce pesticide use. 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 decreases 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.

Although many positive effects of landscape elements and natural habitats on pest control have been observed, either in and around fields or at the landscape scale, the current challenges are to preserve the existing landscape elements and to re-establish or increase introduction to present agroecosystems and agricultural landscapes. Here, habitat thresholds play an important role. 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. Even so, specific recommendations to design appropriate agricultural landscapes that effectively assure biological control are needed.

Integration and management of semi-natural elements at the landscape scale demands multi-stakeholder agreement as this has to be implemented within territorial development. In this respect, this not is a single-operator practice compared to the other agroecological practices presented in this paper.

To summarise, eight categories of agroecological practices can be distinguished that need a redesign of the whole or part of the existing cropping system before they can be adopted. Often, this includes a diversification of the system. Among these agroecological practices are crop choice and rotations; intercropping and relay intercropping; agroforestry with timber, fruit, or nut trees; allelopathic plants; direct seeding into living cover crops or mulch; reduced tillage; integration of semi-natural landscape elements at field or farm scale; and management of landscape elements at landscape scale.

5 Promising agroecological practices

5.1 Scales of application, system change

A broad variety of agroecological practices that improve agricultural production without an expense to the environment or biodiversity have existed for decades. Nevertheless, they are applied to various extents in different parts of the world and to different degrees within the prevailing regional or national farming systems. Whereas agroecological practices are applied by a higher share of farmers practicing integrated agriculture or organic agriculture, wide contrasts are found in conventional agriculture. In most of the highly industrialised large-scale cropping and livestock systems, the use of agroecological practices is still limited. In contrast, in less intensive conventional systems, e.g. in less-favoured hilly or mountainous areas, different agroecological practices have been more widely applied for decades as these areas have lower potential for intensive production.

The application of the different agroecological practices presented in this paper implies modifying the farming system, either at crop management scale or at the cropping or farming system scale. In the case of a single practice, the level of change is usually low because only part of the crop management has to be changed or adapted by the farmer (Table 2). This is usually the case when considering efficiency or substitution practices. For example, applying split fertilisation or changing crop cultivars that can be relatively easily implemented. In contrast, when the practices require modification of the cropping or farming system, the necessary level of system change is normally medium or high because not only a single practice, but a much larger part of the system has to be reorganised or redesigned. For example, direct seeding into living mulch might require a strong system change; new machinery is necessary to prepare fields and carry out seeding, new types of mechanical weed management have to be applied to avoid applying high amounts of herbicides, and crop rotations have to be redesigned to take into account mulch benefits. This high level of system changes explains why this agroecological practice is not yet widely applied in current agriculture.

Table 2 Agroecological cropping practices, scale of application, level of system change, and integration in today's agriculture in Europe

Agroecological practice	Scale of application[a]	Level of system change needed	Level of integration in today's agriculture	Potential for the next decade
Efficiency increase and substitution practices				
Crop choice, crop spatial distribution, and crop temporal succession				
Cultivar choice	Practice	Low	High	High
Crop fertilisation				
Split fertilisation	Practice, system	Low	High	High
Biofertiliser	Practice	Low	Low	Medium
Organic fertilisation	Practice, system	Medium	Medium	Medium
Crop irrigation				
Drip irrigation	Practice	High	Medium	High
Weed, pest, and disease management				
Natural pesticides	Practice	Low	Low	Medium
Biological pest control	System	Medium	Medium	High
Redesign practices				
Crop choice, crop spatial distribution and crop temporal succession				
Crop choice and rotations	System	Medium	Low	High
Intercropping and relay intercropping	Practice, system	High	Low	Medium
Agroforestry with timber, fruit or nut trees	System	High	Low	Low
Weed, pest and disease management				
Allelopathic plants	Practice, system	Low	Low	Medium
Tillage management				
Direct seeding into living cover crops or mulch	System, practice	High	Low	Low/medium
Reduced tillage	System, practice	High	Medium	Medium/high
Management of landscape elements				
Integration of semi-natural landscape elements at field or farm scale	System, practice	Medium	Low	Medium
Management of landscape elements at landscape scale	Landscape	High	Low	Low

[a] Practice=only the specific practice has to be changed or adapted. System=the cropping or farming system has to be changed or adapted. Landscape= multi-stakeholder agreement is necessary to apply management

Diversification plays an important role when implementing many agroecological practices. This is accomplished, for example, with the integration of more diverse cultivars, crops, or intercrops in the cropping system, use of agroforestry systems, and valorisation of semi-natural landscape elements for conservation biological control. The overall objective is to valorise different ecosystem services linked to diversification in order to increase resilience of agroecosystems to perturbation, to decrease pest outbreaks (including weeds) or control them at an acceptable level, and to conserve (agro)biodiversity. Nevertheless, to implement the agroecological practices that are based on diversification, a redesign of cropping systems is often necessary because the general trend after the green revolution was, contrarily, to simplify production systems.

5.2 Integration in today's agriculture and promising agroecological practices

In general, most of the agroecological practices presented in this paper remain today at a low level of application in agriculture (Fig. 7). The two practices that are currently widely applied are split fertilisation and use of cultivars from plant breeding. This seems to be due to their longer existence and the high level of experience and knowledge that have been developed for two or three decades, but also because they do not require a high level of system change (Table 2). Integration of organic fertilisation, cover crops, drip irrigation, and biological pest control has already reached a medium level of integration in today's agriculture. The latter three, together with split fertilisation and the use of plant breeding cultivars, have, in our opinion, a high potential to be more broadly implemented in the next decade because they already benefit from good scientific knowledge as well as broad experience of farmers.

In addition, legislative regulations and laws in Europe or at national levels, such as the Nitrate Directive, Water Framework Directive, Pesticides Framework Directive, the greening of the second pillar of the Common Agricultural Policy in Europe, and agri-environment schemes, will probably boost implementation of more environmentally friendly

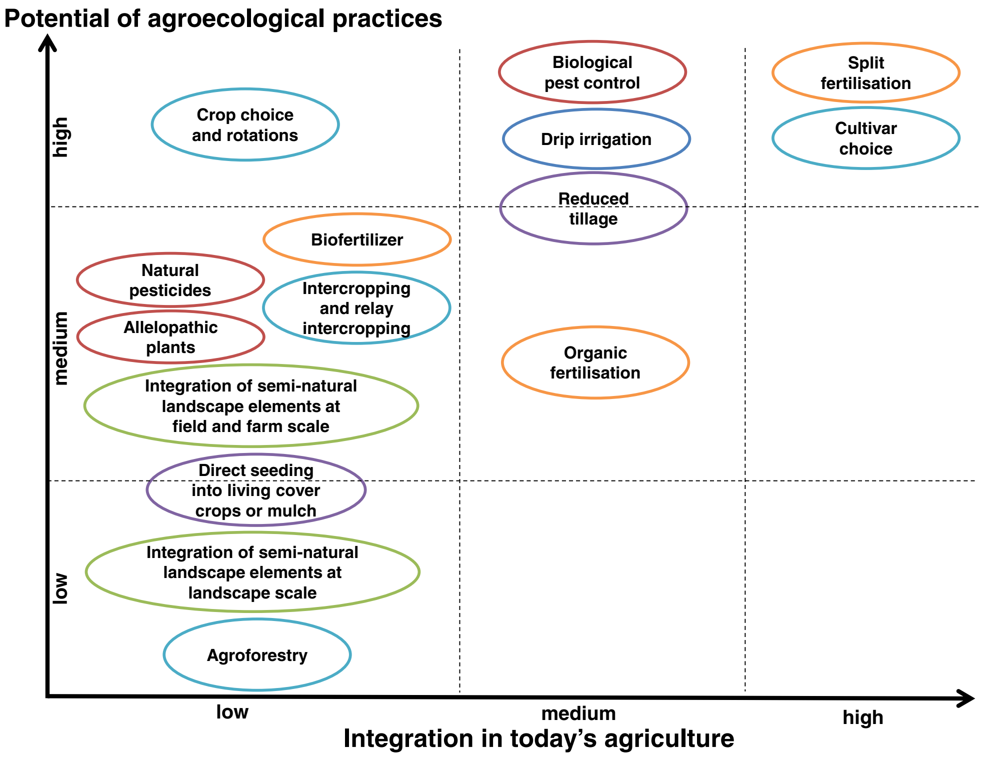


Fig. 7 Potential of agroecological practices for the next decade in relation to their integration in today's agriculture. Most practices have so far a low integration in today's agriculture, and only low or medium potential for the next decade to be more broadly implemented. In contrast, organic fertilisation, reduced tillage, drip irrigation, biological pest control, cultivar choice, and split fertilisation have already medium or high integration levels in today's agriculture, and medium or high potential for the future

practices that are less polluting and less reliant on external inputs. These regulations could enhance an extended use of split fertilisation, cover crops, diversified crop rotation, and biological control.

Nevertheless, most of the agroecological practices only have a medium potential for a broad implementation in the next decade. This is due to still-limited scientific knowledge or low practical on-farm experience with practices such as direct seeding and relay intercropping, and the use of natural pesticides and application of biopesticides in agriculture. A major constraint for direct seeding and intercropping is still their agronomic performance as yields are very variable (Malézieux et al. 2009; Soane et al. 2012). Natural and botanical pesticides as well as biopesticide application will probably not be used on larger areas in the next decade.

In contrast, practices such as direct seeding into living mulch or cover crops and the integration of landscape elements around fields that we classified as medium or low potential for the next decade might even develop much faster than expected as much research is currently carried out on these topics, but also because an increasing number of farmers or farmer groups own the development of these practices.

Integration of allelopathic plants, biofertiliser, agroforestry systems, and management of landscape elements at field scale have a low level of integration in today's agriculture and will, in our opinion, not be broadly implemented in the near future. A landscape-based integration of landscape elements will strongly depend on the regional and national general conditions, as it involves a larger scale of management. Moreover, this type of agroecological practice/approach can probably only be implemented in the framework of territorial development projects and planning. The main constraints for the development of practices based on allelopathy are low scientific knowledge and practical experience, and difficulties to manage allelopathic plants. Although agroforestry systems exist in many European regions, the combined management of trees and meadows, for example, is considered an "old-fashioned" system without high yield potential. The surface areas of these systems are presently decreasing, although some national support programs do exist (Rigueiro-Rodrígues et al. 2009).

What can be generally expected from agroecological practices in the following years? Although some of them are already quite well known, most of them will not be applied in the near future at larger scales. It seems more realistic that we will still have to focus on core production areas with high inputs to guarantee high yields, but in setting clear rules against environmental degradation and pollution as well as biodiversity loss. A broader dissemination of agroecological practices will probably happen first in less-favoured agricultural areas or low potential production zones.

In contrast to temperate zone agriculture, potential for yield increases with agroecological practices are much higher in developing countries as they are usually not at yield maximums, except for irrigated rice systems. Pretty et al. (2003) and De Schutter (2011, 2012) summarised such examples from tropical and subtropical countries. Nevertheless, as in the case for temperate zone agriculture, many of these agroecological practices with high potential in developing countries are not yet widely applied (Altieri 2000; Wezel and Rath 2002).

To summarise, most agroecological practices have so far a low integration in today's agriculture, and only low or medium potential for the next decade to be more broadly implemented. In contrast, organic fertilisation, reduced tillage, drip irrigation, biological pest control, cultivar choice, and split fertilisation have already medium or high integration levels in today's agriculture, and medium or high potential for the future.

6 Outlook beyond agroecological practices

Even in widely applying and further developing agroecological practices, and with this improving agricultural production in terms of quantity and quality, more requirements are necessary to feed the planet by 2050. According to the scenarios developed in the Agrimonde report (INRA and CIRAD 2009), which are based on scenarios of the Millennium Ecosystem Assessment report (2005), it also requires (1) major shifts in food consumption trends, in particular breaking the relationship between higher revenue and higher consumption of animal products; (2) large investments in infrastructure, research, and development not to only increase yields, but to develop agricultural systems that are compatible with ecosystem preservation and resistance to climate change; (3) proactive policies at different levels to improve structural development in agricultural systems and consumption, as well as to regulate food trade; and (4) reducing losses at all levels (storage, transport, processing, distribution, and consumption).

Nevertheless, production practices remain the central and crucial point as they are the primary factor to produce food for future generations. Here, agroecological cropping practices can and should play a central role.

7 Conclusions

Most agroecological practices such as biofertilisers; natural pesticides; crop choice and rotations; intercropping and relay intercropping; agroforestry with timber, fruit, or nut trees; allelopathic plants; direct seeding into living cover crops or mulch; and integration of semi-natural landscape elements at field or farm scale; or their management at landscape scale have so far a low integration in today's agriculture. They have only low or medium potential to be more broadly implemented in the next decade. In contrast, organic fertilisation, split fertilisation, reduced tillage, drip irrigation, biological pest control, and cultivar choice have already medium or high integration levels in today's agriculture, and medium or high potential for the future.

The most important parameters for a limited or broader application today are if (1) the practices have already existed for a significant period of time, (2) there exists widespread farming and good scientific knowledge about the practices, (3) there exists practical on-farm experience, and (4) a system change and redesign of cropping systems is required.

To feed a growing world population, we need practices that provide sufficient food that are not at the detriment or risk to the environment and that assure economic viability for farmers. Here, agroecological cropping practices can and should play a central role.

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