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European Learning Network on Functional AgroBiodiversity

Functional agrobiodiversity

Nature serving Europe's farmers

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About this publication

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About ELN-FAB

The European Learning Network on Functional AgroBiodiversity aims to:

- accumulate knowledge on how biodiversity can be mobilized to increase sustainable agricultural production;
- provide a platform for exchange of knowledge and practical experiences between farmers, policymakers, scientists and other stakeholders;
- enable fast and effective implementation of best practices.

www.eln-fab.eu

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Abbreviations

AES Agri-environment scheme
CAP Common Agricultural Policy
EIP European Innovation Partnership
FAB Functional agrobiodiversity
FAO Food and Agriculture Organization of the United Nations
FAS Farm advice systems
GAEC Good agricultural and environmental condition
GHG Greenhouse gas
IAS Invasive alien species
IPM Integrated Pest Management
WFD Water Framework Directive

Introduction

Agriculture is undoubtedly one of the main driving forces which influence biodiversity in Europe. Agriculture and biodiversity conservation are often described as being in conflict. However, the situation is more complex in terms of interactions between land management and biodiversity.

There is a requirement on the part of society that land management provides private goods, such as food, fibre and fuel, as well as public goods, which are goods that we all benefit from, for example by the services that ecosystems provide to human well-being. Examples of agronomic ecosystem services include pest and disease control, pollination, nutrient cycling, water retention and landscape values. Though these are essential benefits, they are undervalued by the market and proper public payment for delivering such public goods and services is not guaranteed. There is a clear role for public intervention in land management to secure these public benefits.

Functional agrobiodiversity (FAB) uses science-based strategies to optimize regulating, provisioning and cultural ecosystem services that are essential for human well-being. In an increasing number of European countries agrobiodiversity is used as a functional tool for achieving the sustained delivery of ecosystem services. This functional use of agrobiodiversity enhances the sustainability of agricultural production and thus generates additional incentives for farmers to preserve biodiversity. Recent pilot projects in a range of European countries have delivered promising results, including a clear reduction in pest pressure as well as pesticide use on the FAB farms both on a spatial scale and over time.

The aim of this publication is to provide insight into the concept of FAB, its links to agricultural and biodiversity policy and the opportunities offered for a more sustainable agriculture and countryside in Europe. It is hoped that this insight will stimulate a wider uptake of FAB measures across Europe.

What is functional agrobiodiversity?

Defining the concept

The concept of *functional agrobiodiversity* is increasingly being used as a framework in scientific research, policymaking and on-farm implementation.

Functional agrobiodiversity (FAB) refers to '*those elements of biodiversity on the scale of agricultural fields or landscapes, which provide ecosystem services that support sustainable agricultural production and can also deliver benefits to the regional and global environment and the public at large*'.*

FAB uses science-based strategies to optimize regulating, provisioning and cultural ecosystem services (Figure 1). Positive synergies often exist among regulating, provisioning and cultural services and with biodiversity conservation.

The concept of FAB is therefore not synonymous with farming systems or broad agricultural concepts such as 'environmentally friendly agriculture', 'sustainable agriculture', 'organic farming', or 'multifunctional agriculture'. However, FAB can certainly be an element of such systems, in the same way that it can be an element of conventional farming systems or integrated landscape management. The difference lies in that FAB emphasizes the application and development of informed management practices that specifically enhance and exploit elements of biodiversity for their role in providing ecosystem services, irrespective of the type of farming system(s) they are being applied to.

In general terms, a guiding principle in FAB is to use external inputs in a rational way, building on biological regulation where possible.

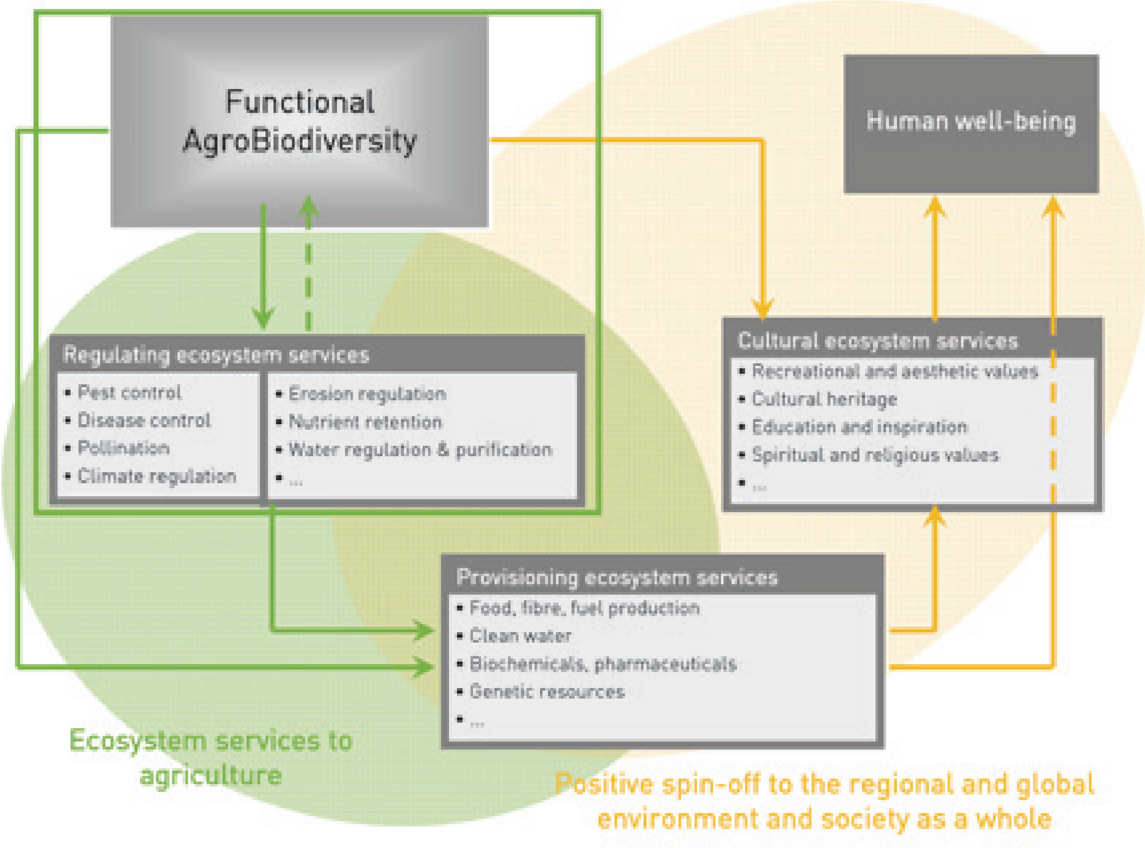


Figure 1: Conceptual diagram showing the relationships between FAB and ecosystem services with benefits to agriculture and society as a whole. (Adapted from the Millennium Ecosystem Assessment, 2005)

* European Learning Network on Functional AgroBiodiversity - www.eln-fab.eu

The interactions between agriculture and agrobiodiversity are complex, and measures to improve these interactions are very diverse. Four spheres of interactions can be distinguished:[1]

- FAB that includes all biodiversity in an agricultural landscape that delivers or can deliver a positive contribution to the productive function of agriculture via: (1) the improvement of soil quality; (2) crop pollination; (3) biological pest control; (4) influence on microclimate; and (5) the availability of genetic diversity.
- Competitive agrobiodiversity is responsible for pests, plant diseases, weeds and wildlife damage.
- Agrobiodiversity also provides an important contribution to the delivery of ecosystem services from rural areas that are of importance to society, such as water purification, water infiltration, water storage, erosion control, carbon sequestration, attractive landscapes, and habitat for species which are valued by society.
- On the other hand, land-use and agricultural practices can exercise a strong positive or negative impact on agrobiodiversity. Measures that can improve the impact of agriculture on agrobiodiversity are related to improvement of the environmental quality (related to soil carbon content, water levels, nutrient concentrations); the provision of food sources and reproduction habitat between and within agricultural parcels; rational use of pesticides and veterinary pharmaceuticals; countering of habitat fragmentation; and increasing the variation of landscape structure and environmental conditions.

Considering these interactions, agro-environmental measures can be broadened from a narrow focus to a certain number of farm species or specific environmental goals, to include functional and competitive biodiversity and ecosystem services. This more holistic approach will also affect agricultural production in a positive way, and can provide additional incentives to farmers to participate (besides the purely financial incentives).

The benefits

In an increasing number of European countries targeted agrobiodiversity schemes are used as a functional tool for achieving the sustained delivery of ecosystem services such as natural pest control, pollination, nutrient cycling and water retention. Recent projects in a range of European countries have delivered promising results, including a clear reduction in pest pressure as well as in pesticide use on farms. This,

Important relationships between agriculture and FAB which could be taken into account by agro-environmental measures[1]

FAB supports agricultural production:

1. **Development of favourable soil quality**
   Soil organisms ensure the maintenance and development of good soil structure, with positive effects on water regulation, erosion, leaching, etc. In addition, a healthy soil ecosystem ensures the release of nutrients and better disease resistance, which are essential to good crop development.
2. **Crop pollination**
   Crops are mainly pollinated by honeybees, which are introduced for this purpose by beekeepers or in collaboration with them. Wild agrobiodiversity also plays an important supplementary role. A significant portion of fruit production is dependent on pollination by insects.
3. **Biological pest control**
   Natural enemies of plague insects can help to keep them below the damage threshold, so that the use of crop protection products is limited or not necessary.
4. **Natural and semi-natural vegetation in the agricultural landscape**
   Natural vegetation can help in erosion control, relieve heat stress in cattle, etc. It also provides a habitat for other useful organisms, such as natural enemies of plague species, and it determines the appearance of the landscape.
5. **Genetic diversity as a prerequisite for the ability to adapt**
   It is vitally important to maintain genetic diversity, in order for agricultural crops and livestock to be able to adapt – naturally or with human intervention – to future needs and challenges.

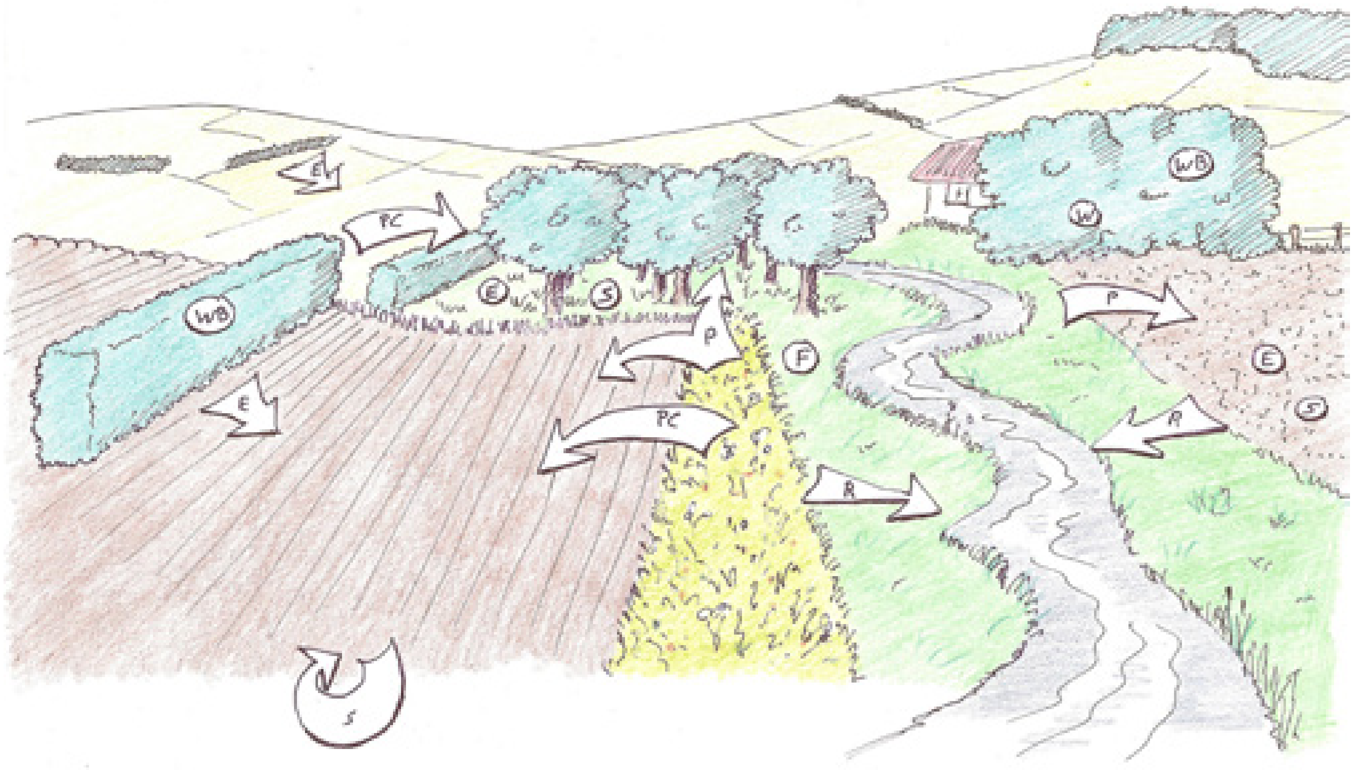


Figure 2: How FAB provides multiple ecosystem services in an agricultural landscape. (Drawing: Ben Delbaere)

together with other examples of benefits as presented below, illustrates that introducing and maintaining the right biodiversity elements is essential for sustaining the ecological functions that ensure agricultural productivity and the sustainable use of natural resources. By recognizing biodiversity as a key element of agricultural production, and by understanding which biodiversity elements generate ecosystem services, tools can be generated for farmers to make their production systems more robust to disturbances and less dependent on external inputs. This will be essential to ensure the delivery of safe and sufficient food, fibre and fuel, as well as public environmental services that all Europeans benefit from.

Finding the right balance between the delivery of 'non-productive' ecosystem services from agricultural land, such as water quality, pollination, valued landscapes and of course biodiversity itself, and the creation of favourable conditions for producing crops with fewer inputs (e.g. fertilizers and pesticides) is a challenge and in fact a strategic decision with long-term benefits. In particular, the EU 'green growth' agenda may offer opportunities to biodiversity both through the development of green technologies (like FAB) that can limit agriculture's impact on the environment, and through wider economic initiatives, for example sustainable tourism, on-farm biodiversity management activities, high value-added products linked to farming practices which protect biodiversity, sustainable leisure developments which celebrate and protect biodiversity, etc. Perhaps more fundamentally, biodiversity, especially with regard to healthy soils, delivered by FAB, is also critical for the long-term productivity and sustainability of agriculture and will therefore play a key role in ensuring food security in the future.

Multiple ecosystem services

Figure 2 above presents a schematic overview of a number of services offered by biodiversity components, in a hypothetical European landscape. It demonstrates that services act at various scales (within farm plot, with adjacent plots, and at a wider landscape scale), and that single elements may provide multiple services and benefits.

E: Erosion prevention. Hedgerows that follow the lines of altitude prevent soil erosion further downhill. Grassy and herby vegetation cover in orchards, vineyards or olive groves prevents soil from being eroded by wind or heavy rainfall. Leaving stubble on arable land has a similar effect.

F: Flood prevention. Leaving low-lying river banks out of agricultural production and covered with short vegetation provides room for excess water and slows down water speed, protecting (agricultural) land further downstream.

P: Pollination. Flower-rich field margins, vegetated river banks, small woods and other features provide natural habitat for a range of insect species that act as essential pollinators for arable fields, orchards and other crops.

PC: Pest control. Flower-rich field margins (with selected seed mixtures) and other semi-natural landscape features offer habitat for natural enemies of agricultural pest species. Hedges, small woodlands and other elements also provide habitat for predators and raptors that keep small rodents in check.

R: Run-off reduction. Leaving strips of land around arable fields vegetated captures excess nutrients and pesticides and prevents them from running off into ditches and rivers.

S: Soil structure and function. Reduced tillage, leaving stubble on the field and other measures that prevent unnecessary disturbance of the soil increase soil biodiversity, which in turn increases soil structure, aeration, nutrient capture and release.

W: Water retention. Vegetated land along rivers and small woodlands acts as a sponge that holds water during high water levels and gradually releases it over a longer period of time.

WB: Windbreak. Landscape features such as hedge-rows, tree rows, woodlots or orchards reduce local wind speed, which in turn reduces wind erosion and prevents sensitive crops from being lashed by heavy winds. In certain situations local agricultural production levels near the windbreaks increase.

Biodiversity is the basis of life-support systems. Pollinators, predators, soil biota and all other organisms that support the productivity of agro-ecosystems have particularly important benefits, allowing agriculture to produce food. In addition, biodiversity allows farmers to produce non-food products, as well as services.

As already described above, multiple ecosystem services provide multiple benefits, not only for the agricultural sector, but also for society as a whole:

Example of FAB-based practice	Types of ecosystem services provided	Benefits for farmers or society as a whole
Provide habitat and resources to pollinators on farmland, through implementation or conservation of semi-natural landscape elements	Pollination	Increased yields and quality of farm crops that require pollination; landscape aesthetics
Mixed rotations	Biological pest and disease control; increased soil fertility	Reduced costs of external inputs; reduced environmental impacts; reduced pesticide residues; landscape aesthetics
Field margin management to provide alternative food sources and overwintering sites for pest natural enemies	Biological pest control	
Hedgerows	Soil and water conservation	Reduced soil erosion and water loss; less damage to infrastructure; landscape aesthetics
Reduced tillage for enhancing earthworm numbers and diversity	Maintenance of good soil structure; nutrient cycling	Improved water infiltration; less waterlogging; reduced soil erosion
Use of green manure cover crops, including legumes	Maintenance of good soil structure and nutrient cycling by a diverse community of soil organisms; retention of nutrients	Reduced dependence on external inputs; reduced environmental impacts
Production of rare, traditional crops, cultivars or animal breeds	Conservation of plant or animal genetic resources	Improved income from value-added specialty products; future adaptive capacity and resilience to disturbances

Financial compensation system for farmers delivering public environmental goods based on compensation for the losses incurred in meeting the requirements of agri-environment scheme (AES) prescriptions.[2] Farmers managing small agricultural units often see transaction costs as particular obstacles to participating in AES. Measures to reduce the transaction costs which deter uptake would include simplifying application processes and payment schemes for farmers, and redistributing private costs to public transaction costs, for example, through publicly-funded advice networks.[3]

The interplay between European agricultural and biodiversity policy

Agriculture influences biodiversity

In recent decades there has been growing awareness and recognition in different sectors of society that the conservation and sustainable use of biodiversity is key to human well-being. Biodiversity plays a pertinent role in the provision of ecosystem services, including those that are essential to sustainable agricultural production. Wild plants and animals, the cornerstones of biodiversity, are the origin of all crops and domestic livestock and the variety within them. In addition, components of biodiversity in agricultural landscapes maintain ecosystem services such as pollination, biological pest control, soil and water conservation, nutrient cycling, and climate regulation.

Modified landscape management and alternative farming practices can contribute to biodiversity conservation in various ways. However, biodiversity in and of itself does not automatically translate into ecosystem services such as enhanced pollination or natural pest control. To optimize these benefits, we need to understand which biodiversity elements drive these ecosystem services. Based on this information, benefits to farm productivity can be generated through a rational design and management of agro-ecosystems and landscape structures. Such management strategies can range from informed choice of non-crop vegetation such as field margins, forests, hedgerows and other non-crop elements, to conservation tillage, crop diversification or crop rotation.

Non-crop vegetation such as field margins provides benefits to farm productivity. © VLM.

Agriculture is undoubtedly one of the main driving forces which influence biodiversity in Europe, as about half of the EU territory is under agricultural use. Recognition of the strong links between biodiversity and agriculture is reflected in policy frameworks at the EU and national levels. So far, environmental policies in the EU have primarily focused on negative impacts of agriculture on biodiversity and ways to alleviate them. More recently, European farmers and policymakers have increasingly recognized that agricultural production and biodiversity need not necessarily be in conflict, but are interdependent and can strengthen each other. In response to these changing perspectives policymakers have started to integrate ecosystem health into some sectoral policies with a focus on harnessing synergies between biodiversity conservation and sustainable production.

Challenges to Europe's agriculture

Today the world is facing a number of challenges, several of them directly affecting agricultural production in Europe. One of the major challenges is how to meet worldwide rising food demand and changing consumption patterns whilst facing up to finite land and water resources, the decline in biodiversity, the effects of climate change and the increasing rate of extreme weather events. In addition, this all should be achieved in a more sustainable way, including by protecting natural resources and biodiversity. Also, soil sealing and the consumption of land by urban sprawl and infrastructure are having damaging consequences for biodiversity and landscapes, because of the increasing number of habitats and area of prime agricultural land that are being lost and fragmented. Increasing production costs in agriculture, in particular for inputs, and the prevalence of market turbulence and price volatility are putting extra pressure on farmers, who are in addition faced with ongoing globalization and trade liberalization. In addition, farmers are the weakest link in the food supply chain and they are confronted with the huge bargaining power of retail companies further down the chain. In future, increasing food production alongside environmental improvement can and must go hand in hand if the growing global human population is to be fed. Farmers in the EU have a major task ahead – producing more but impacting less.

In this context it is of major importance to find solutions in order to keep farming in the EU competitive, aligning the economic interests of farmers with biodiversity goals. This is a prerequisite for a viable farming sector able to provide commodities as well as environmental goods and services.

A strong interdependency exists between healthy ecosystems and sustainable agricultural production. Therefore, farmers should be interested in maintaining a good ecological status on their land to secure their long-term productivity. Assuring sustainable land use while maintaining a profitable farming sector contributes not only to the livelihood of rural areas, but also to the preservation of habitats and species that depend on farmland, to the maintenance of genetic diversity and to the avoidance of land abandonment on a large scale.

The Common Agricultural Policy and the environment

Although in recent decades there has been a trend towards increasing intensification and larger farm units in all EU Member States, the diversity of farming systems remains large and the level of industrialization is much lower than that of many other developed countries in the world. This is partly due to the large heterogeneity of biogeophysical conditions across Europe, but it is also the result of the EU Common Agricultural Policy (the CAP), which has been reformed several times and is shaping European agriculture.

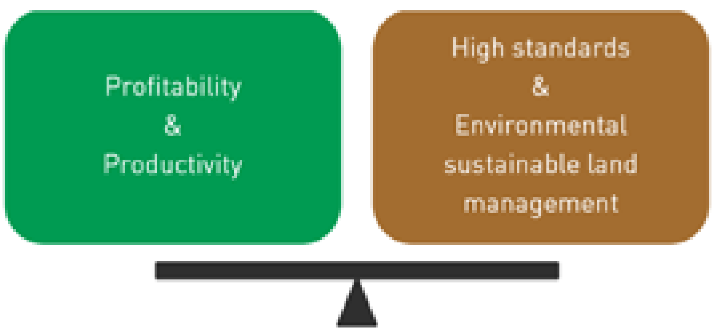


Figure 3: Balance between economic interests and environmental goals.

Multifunctional landscapes deliver multiple ecosystem services. © Arnaud Bouissou, METL-MEDDE.

Originating in the late 1950s, the CAP sets the framework for all agriculture in the EU. Every reform of the CAP (and in particular those since 2003) has put an increased emphasis on environmental improvements in agricultural production. Focus on less intensive systems and the introduction of cross-compliance are part of this approach. Cross-compliance is a mechanism introduced as part of the 2003 CAP reform in which financial support to farmers is linked to compliance with environmental, food safety, animal health and welfare regulations. In addition to these statutory management requirements, farmers have to maintain land in good agricultural and environmental condition (referred to as GAEC). These agricultural production standards address soil protection, maintenance of soil organic matter and structure, preventing soil erosion and avoiding the deterioration of habitats, and since 2010 include water protection and management. Another cross-compliance obligation is the protection of permanent pastures and the maintenance of the permanent pasture ratio (the share of permanent pasture relative to an agreed reference value).

For the period 2014–2020 the proposals for the CAP* foresee the introduction of payments for agricultural practices that are beneficial for the climate and the environment (called greening) in addition to the continuation of cross-compliance. It is proposed that farmers will receive full payments only if the following three measures are implemented: crop diversification; maintenance of permanent grassland at farm level; and the establishment of ecological focus areas. The latter measure in particular offers opportunities for conserving biodiversity while at the same time strengthening ecosystem services that support sustainable agriculture. While there is no doubt that these measures can support biodiversity conservation, it is not at all certain that farmers who adopt this approach will take the specific local requirements of species sufficiently into account and look for win-win solutions such as those offered by FAB. If these obligations are too burdensome for farmers, resulting in them giving up the production of certain commodities or giving up farming entirely, this may lead to translocation of intensive production outside the EU with disastrous consequences for biodiversity in developing countries in particular if mismanaged.

Besides these proposed mandatory greening measures, voluntary agri-environmental schemes as part of the Rural Development Programmes will remain in the future CAP. The proposal envisages enlarging their scope to cover climate as well as the possibility for group commitments in order to improve the effectiveness of these measures. By adopting voluntary environmental measures at farm level, farmers are compensated for the additional costs and/or income forgone. Agri-environmental measures can contribute positively to the protection of landscapes, soils, water and biodiversity. Voluntary environmental measures, such as grass buffer strips, skylark plots and flower strips, can be adopted on farmland. A major obstacle is that in the EU less than 15% of farms are wholly owned and in many of the new Member States more than a quarter of agricultural holdings have no owned

* http://ec.europa.eu/agriculture/cap-post-2013/legal-proposals/index_en.htm

land at all.* Being involved in a tenancy arrangement, in particular in the case of short-term contracts, can be a key obstacle for participation in multiannual agri-environmental schemes. In addition, it can hamper the uptake of alternative, more environmental farming practices if it pays off only after several years.

Biodiversity and environmental pollution

The EU flagship initiative for a resource-efficient Europe[4] provides a long-term framework for actions in many policy areas, supporting policy agendas for climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development. Striving for resource use efficiency means not only reducing the use of carbon-intensive fossil fuels to bring down greenhouse gas (GHG) emissions, but also increasing efficiency in the use of minerals, biomass, land and water.

Several European directives are indirectly concerned with agriculture and biodiversity conservation.

Biodiversity and sustainable water management are closely interlinked. Therefore improvements in qualitative as well as quantitative water management arising from the Water Framework Directive (WFD) will bring benefits to inland as well as freshwater and marine biodiversity. The WFD (2000/60/EC) establishes a legal framework to prevent further deterioration of and to protect, enhance and restore waters with the aim of achieving 'good status' of all Community waters by 2015. Besides this framework directive, there is specific legislation targeting pollution caused by agricultural activity. Biodiversity on farmland as well as in the wider environment is affected by nutrient inputs and the use of plant protection products. In order to minimize negative impacts, specific EU legislation exists.

Good soil fertility is the basis of sustainable farming and one of the main 'capital inputs' for the future of food provision as well as for the sequestration capacity of carbon dioxide. In recent decades soil fertility in Europe has been deteriorating. The European Commission adopted a Soil Thematic Strategy (COM(2006) 231) and a proposal for a Soil Framework Directive (COM(2006) 232) with the objective of protecting soils across the EU.

Maintaining soil fertility is central to the productivity of agricultural land now and in the future. FAB provides practices which contribute to improved soil fertility.

Other directives relate to pollution prevention. The Nitrates Directive (91/676/EEC) targets nitrogen and in particular fertilizer practices, with the intention of reducing nitrogen losses to the environment, and thereby reducing the risk of eutrophication in aquatic and terrestrial ecosystems, together with its associated negative impact on animal and plant species.

An integral part of the Sustainable Use of Pesticides Directive (2009/128/EC) is the concept of Integrated Pest Management (IPM). Article 14 (1) states 'Member States shall take all necessary measures to promote low pesticide-input pest management, giving wherever possible priority to non-chemical methods, so that professional users of pesticides switch to practices and products with the lowest risk to human health and the environment among those available for the same pest problem.' This has to be complemented by improved and easy to apply monitoring and prediction tools to allow forecasts to reduce uncertainties, with special focus on the regional scale. For example, access to early warning systems and weather databases is an essential prerequisite to change from preventive application of plant production products to biological pest control. In order to implement the Sustainable Use of Pesticides Directive all Member States prepare national action plans with detailed requirements for the farmers. FAB provides an excellent opportunity to contribute to the Directive's objectives by offering biological pest control solutions.

Education and training for farmers

It is essential and will become even more important to support farmers in combining high-yield and sustainable, efficient, environmentally friendly farming. European farmers will be able to respond to society's demands only if they have the necessary know-how and if sufficient incentives are provided for sustainable investments. Therefore, it is essential to provide the necessary knowledge and skills. The CAP offers the possibility to offer environmental advice as part of the Farm Advice Systems (FAS). In the proposals for the future CAP the scope is broadened and there is more emphasis on advisory and vocational training for

* Eurostat 2007.

environmentally sustainable agriculture. This has to be supported by research and development of innovative technology and management practices (with a focus on the efficient use of natural resources). Education and training about the potential of applying FAB could become part of the regular advisory services.

In order to boost innovation in this area, to make research more problem-oriented and to speed up the uptake of innovative solutions by the farming sector, the Commission has set up the European Innovation Partnership (EIP) 'Agricultural Productivity and Sustainability'.[5] The EIP will contribute to improving the understanding of agro-ecologic interactions and look for solutions on how to resolve the apparent contradictions between improving the efficiency of animal and plant production on the one hand and ecological sustainability on the other. The pace of successful uptake of innovation by farmers and agri-cooperatives is closely linked to the future market opportunities such innovation offers. When dealing with measures which have only minor commercial value or are not rewarded by the market at all, as is often the case for improved environmental practices, support from public authorities is of great importance. A targeted use of the 'collaboration', 'knowledge transfer' and 'non-productive investments' measures, as proposed under the Rural Development Programmes in order to promote biodiversity-friendly technology and practices, may be an option.

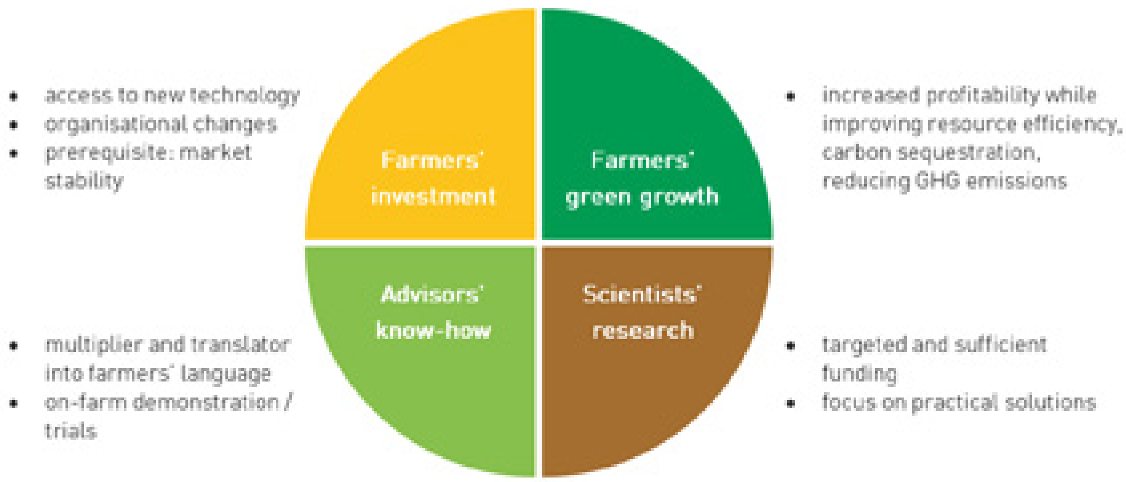
The EIP aims to contribute to correctly identifying the environmental needs, taking into account regional

Knowledge transfer in a FAB pilot project. © ZLTO.

differences, to help farmers in their decision-making, especially in cases where there are conflicting goals for the different natural resources and biodiversity. Whenever possible, priority will be given to environmental improvements that provide synergies. Priority should also be given to innovation that will support the efficient use of natural resources and protect biodiversity whilst keeping farming economically viable.

With their many years of local knowledge and experience in land management, farmers themselves can play an important role in identifying suitable agricultural management practices which are beneficial to biodiversity. The involvement of farmers via applied research and the implementation of on-farm trials can contribute to the continuous improvement of environmental impacts from farming activity. Figure 4 shows the conceptual framework for reaching win-win solutions.

Figure 4: Call for win-win solutions which enable farmers to contribute to a better environment, but which also have a positive impact on their productivity and profitability.



Turning international agreements into local action

One of the important trends of the 20^{th} century was increasing globalization and internationalization. This is continuing into the current century in fields such as trade, tourism, economy and policy development. Most policy and legislation these days is agreed in an international setting, be it between two countries, or across the EU, an entire continent or the entire globe. This is true for bilateral and global trade agreements involving the World Trade Organization concerning agriculture in the EU. It is also true for biodiversity, for which the UN Convention on Biological Diversity provides the global framework and the EU 2020 Biodiversity Strategy and related nature directives provide the EU policy instruments.

With the EU 2020 Biodiversity Strategy[6] the Commission has taken a strong stand with a view to halting the loss of biodiversity and ecosystem services in the EU by 2020 and restoring them in so far as feasible. A specific target has been set for sustainable agriculture, which states: 'By 2020, maximise areas under agriculture across grasslands, arable land and permanent crops that are covered by biodiversity-related measures under the CAP so as to ensure the conservation of biodiversity and to bring about a measurable improvement in the conservation status of species and habitats that depend on or are affected by agriculture and in the provision of ecosystem services as compared to the EU 2010 Baseline, thus contributing to enhance sustainable management.' In order to achieve this target three of the actions will address:

1. the provision of environmental public goods;
2. the use of Rural Development for biodiversity conservation;
3. the conservation of genetic diversity.

In line with the objectives of the EU 2020 Biodiversity Strategy the EU Commission is developing a Green Infrastructure strategy and a dedicated invasive alien species (IAS) legislative instrument. Both are likely to lead to additional attention on biodiversity in Europe, including on those species associated with agricultural land.

In its resolution of 20 April 2012 on the EU Biodiversity Strategy 2020, the European Parliament gives a lot of attention to agriculture. It calls *inter alia* 'for a reorientation of the CAP towards the provision of compensation to farmers for the delivery of public goods, since the market is currently failing to integrate the economic value of the important public goods agriculture can deliver'.

The Natura 2000 network is a core element of EU biodiversity conservation policy, covering approximately 17% of the EU land surface, with large differences across the Member States. It was established under the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC, amended from 79/409/EEC). The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats. In these protected areas, protection status has to be maintained at least at current levels, while farming activity can, under certain conditions, still be pursued. All in all, 38% of Natura 2000 is covered by agro-ecosystems.[7] The Commission is preparing an EU guidance document on management of farmland and Natura 2000 in order to look into challenges and opportunities and ways and means to improve cooperation between the farmers and the nature conservation community.

The importance of nation states and intergovernmental organizations (such as the United Nations, the Council of Europe, and the European Union) continued to grow until roughly the 1970s. This was a period of increasing international policy development, particularly in the case of biodiversity. The bulk of international biodiversity policy was developed and agreed in the period from 1970 to mid-1990. Since then, there was growing recognition that enough international decisions had been made and enough treaties had been signed. There was a growing awareness that it was time to move to implementation and to actively deliver the biodiversity goals that had been agreed. This meant that the role of regional and local stakeholders gradually started to increase, because this is where the action is: these parties implement the internationally agreed objectives on the ground.

For biodiversity in general, local biodiversity action plans became an important tool in supporting this process of regionalization and facilitating local stakeholders. For biodiversity in an agricultural context, local and regional initiatives developed in response to the need for local implementation of biodiversity, and agricultural, goals. In many European countries collaboration platforms were established to cooperate with farmers from the same region as well as with other regional stakeholders. In several cases measures based on FAB were integrated into these activities and proved to be an excellent tool for local action in support of international ambitions.

FAB approaches in local actions[8]

In the Netherlands, researchers have developed and tested planning methods by which local stakeholder groups aimed to provide landscape services through green infrastructure. This research revealed how farmers, water managers and environmental groups discovered how green infrastructure can be of common interest, because it provides benefits to a range of stakeholders. For example, it can lead to simultaneous improvement of biodiversity and the cultural identity of the landscape. It also showed how planning for landscape services helps people to focus on opportunities rather than on problems.

In the Hoeksche Waard polder, near Rotterdam, green infrastructure is now being reconstructed in order to improve pest regulation in crops (provided by insects that live in the adjacent green infrastructure), purify the surface water and strengthen the recreational quality of the area. Farmers are proud to show tourists how biodiversity allows them to grow sustainable crops, using much less pesticide, while the water board also needs to carry out less water purification. The local environmental group, meanwhile, is happy with the increase of biodiversity in the landscape. Moreover, a surprising outcome of this planning process was that social interactions also became stronger.

Many questions about how to mainstream biodiversity in community-based planning remain unanswered; for example, the role of the government and how large business partners can be interested in investing in the local landscape. Some critics warn that emphasizing the user benefits of biodiversity will eventually lead to impoverished ecosystems. Better understanding is also needed of how local green infrastructure networks support large-scale ecological processes that contribute to reaching the goals of the EU biodiversity policy. New studies in North-West Europe will provide some of the answers to these issues. Several provinces in the Netherlands have started a common programme to find out how green infrastructure planning by local stakeholders can create connectivity zones within the European Natura 2000 network. It is essential to conduct and learn from such experiments in order to find a manner to safeguard the conditions for biodiversity and a sustainable society.

Treelines in an intensive agricultural area are part of the green infrastructure. © Laurent Mignaux, METL-MEDDE.

How to integrate FAB into farming practices

Pollination

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Pollination – the indispensable ecosystem service in agriculture

Humankind benefits from a wide range of natural ecological functions, which are known as ecosystem services. Pollination by wild animals is considered to be a key ecosystem service and insects are recognized to be the most important pollinator group. Animal pollination is thought to benefit the yields of 75% of globally important crop species and is responsible for an estimated 35% of world crop production.[9]

Pollination services are provided by managed and native pollinators. Bees (Apidae) are generally considered the most important pollinators; a substantial proportion of agricultural pollination services are attributed to the domesticated European honeybee (*Apis mellifera*).[10] Still, there are more than 20,000 native bee species worldwide that make a vital contribution to crop pollination and are often more effective pollinators than honeybees. They play a crucial role in the production of certain fruits, vegetables and forage crops such as red clovers, lucernes, melons, cranberries, blueberries, soybeans, field beans and sunflowers.

The economic value of insect pollination services to crop agriculture has been estimated at £400 million per annum within the UK[11] and US$153 billion per annum globally.[12]

For sustainable agriculture it is important to preserve the stability of pollination services. Although the number of global honeybee hives has grown by about 45% since 1961, the area of insect pollinated crops has grown by over 300% in the same period.[13] While trends in global yields do not demonstrate any significant global pollination shortage so far,[14] regional declines have been associated with localized shortfalls in pollinator populations.[15] Within Europe, the UK has experienced particularly well documented pollinator losses, with widely recorded declines in the diversity and distribution of native pollinators and a 54% fall in honeybee hive numbers in England between 1985 and 2005,[16] raising concerns over the long-term stability of UK pollination services. The same trends can be seen in many other European regions.

Farmers' challenges

Reduction in pollination services results in reductions in productivity, yield and crop quality, which in turn often lead to reduced net farm income.

Decline in yields due to lack of pollination

Pollination service guarantees an important part of annual yields of different crops. For example, oilseed rape is the sixth most important crop in Europe with nearly 8.8 million hectares under cultivation and the second most important oilseed crop after sunflower seed.[17] Forecasts predict a continuing increase in demand for oilseed rape production in Europe. The crop has high yield potential under efficient economic cultivation. The lack of adequate pollination of oilseed crops decreases the yields by up to 25%.[18] Cross-pollinated flowers produce seeds with higher weight (up to 14%), more seeds per pod and more pods per plant. Furthermore, the ripening of the seeds is more even in time and there are fewer losses during the harvest.

Decline of available pollination service

Widespread declines of pollinators have received particular attention because of the risk to food security, wild flora and associated biodiversity. Continued declines in pollinator activity could mean rising costs and falling availability and quality of pollinator-dependent fruits, vegetables and other crops. The dramatic decline in pollinator populations is a critical issue for production agriculture, but it is not yet on the top-priority list for many agricultural organizations.

Despite growing demand for pollination services and rising numbers of domestically managed honeybee colonies, the number of hives for optimal pollination service has declined by more than 50% since 1984 and will fall further if recent honeybee declines are considered.[16]

Chemical pesticides,[19] land-use changes and introduced diseases and parasites are considered reasons for pollinator declines. These factors have caused instability of honeybee populations and thus of the pollination service. For instance, in the UK only about 2% of hives are known to be professionally managed for pollination services.[20] The low pollinator availability has increased hive rental fees.

The free services from native pollinators could account for a substantially greater proportion than previously thought, even in modern, intensive farm systems.[21] Unfortunately, native bee populations are now thought to be in a long-term state of decline in intensive agricultural areas.[22] Native bees cannot be replaced by honeybees, since they are not able to pollinate all crops adequately. Many leguminous crops do not benefit from honeybee flower visitation. Red clover and field bean need long-tongued bumblebees, which pollinate the flowers much more effectively than honeybees do. For lucerne (alfalfa), solitary bees are the most efficient pollinators, although some short-tongued bumblebee species can also perform well.

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The lack of adequate pest control products which are less harmful to the non-target fauna

Pesticides are also a major threat to insect pollinators. For bees, hazards vary widely between products. Registration requirements cover only direct toxicity tests, and thus overlook sublethal effects, which have recently been linked to pollinator declines.[19; 23] There are several ways to reduce the harmful effect of pesticides on bees, the most important being to avoid using harmful pesticides on insect-pollinated crops before flowering. It is claimed that some chemical products have a repellent effect on bees. Biopesticides can be a suitable alternative, but not all of these are safe for non-target insects. More compatibility studies are required to assess non-target effects, including sublethal effects on pollinators.

Classical solutions

In contemporary intensive farming, the following measures are most often applied to ensure delivery of pollination services:

Supplementary honeybee hives transported to fields, orchards, etc.

- Sufficient numbers of pollinating bees around the crops guarantee quality and increased yield, thereby enabling economic profit.
- Traditionally apiaries have static sites (often small scale). They are not able to cover all agricultural areas with a sufficient number of bees. In addition, the fields with monocultures do not provide enough food for all through the season.
- Large-scale honey producers practice migratory beekeeping. This is most likely to be profitable where large areas of land, accessible by road, support plants that are honey sources and that flower at a specific and predictable time each year. Migratory beekeeping in Europe is practised in France, Spain, Germany, Greece, Italy and the UK. The migratory pollinators might not be available everywhere.

Use of commercially produced non-*Apis* pollinators

- Beside free native pollinators it is possible to buy commercially managed non-*Apis* bee species (bumblebees, solitary bees, etc.) to enhance pollination effectiveness.
- It is advisable to use native insect species for this, to avoid competition with local native pollinator populations.

Regulation of pesticide handling methods

- Avoid insecticide application during the flowering period of the crop or other plants that attract bees in or near the fields.
- In the case of persistent systemic pesticides, application before flowering can also affect pollinators.
- Timing (e.g. evening application of products with contact activity).
- Strictly follow the threshold levels for controlling the pests.
- Avoid misuse of agricultural chemicals.
- Enhance the yield through self-compatible cultivars (this requires plant breeding).

Honeybee attractants are products designed to increase bee visitation to treated crops with the purpose of increasing the rate of pollination. The main idea is to lure bees away from competing blooms and/or improve their efficiency in flowers with poor attractiveness to bees. Bee attractants encourage bee visitation but not necessarily bee pollination. The most promising products are based on synthetic honeybee queen mandibular pheromone.[18]

Hand pollination is a technique used if open pollination is insufficient or undesirable. It is applicable only on a small scale and in greenhouses for certain cultures. In addition, it also requires specific knowledge of the floral biology.

FAB solutions

Many simple and relatively inexpensive practices for pollinator conservation are available. The following solutions may be applied (alone or in combination) to strengthen pollination services based on FAB.

Enhance free pollination service

Diverse landscapes provide bees with better hibernating, nesting and foraging opportunities than intensively managed homogeneous fields.[24] The results of several studies have shown that greater abundance and species diversity of bumblebees are found in smaller fields with higher crop diversity and heterogeneous landscape.[25;26;27;28] The botanical composition of the flowering vegetation is an important factor in terms of delivering pollinator benefits.[29]

Ensure food for pollinators

Small-scale fields. The size of the field has an important influence on the number of bumblebees present, since many bumblebees have a limited foraging range, which for some species is restricted to only 450 m.[30] This might be one explanation for why many bumblebee species with shorter flight distances

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have disappeared from intensively farmed open areas.

Flowering patches, field edges. Native and managed bees cannot survive if food is not available throughout the foraging season. Therefore, flower-rich field margins of different native wild flowering plants should be created. Many bumblebee and other bee species have very narrow and specific food demands. Some more specialized species depend on the presence of certain food plants more than others. For example, long-tongued bumblebee species have suffered the strongest declines. This is at least partly connected to the shift in agricultural plants grown on farms. Traditionally hayfields consisted of different wild plants, including a lot of flowering plants, but nowadays in cultural hayfields with intensive management carefully chosen graminaceous species are grown. Also, the traditional hay contained very many leguminous plants, which constitute the major part of pollen collected by long-tongued bumblebees. Having clovers and/or other leguminous plant species in crop rotation systems enhances the pollinator community.

Seed mixtures. Wildflower mixes can also be used in field margins to support the food resources during the periods when crops are not flowering. Those unmanaged flower patches also support the formation of more abundant bee populations by connecting separate natural areas with each other. For this purpose, it is crucial to identify the most suitable seed mixtures consisting of native plant species for each country. It is advisable to assess the seed mixtures available on the market and if necessary see if non-native species can be replaced by natives. In addition, farmers can also collect seeds of wild native flowering plants from nature and seed them to field margins.

Ensure nesting and hibernating sites

For the provisioning of nesting and floral resources, wild pollinators often depend on natural and semi-natural habitats: tree cavities, stone walls, suitable soil substrates, etc.

Restore/maintain flowering meadows. Bumblebees are associated with wildflower-rich semi-natural habitats, such as permanent unimproved grassland, which provide both nesting and foraging resources.[31] For example, some of the most biodiversity-rich habitats have been recorded on old, regularly mown temperate

Small-scale cultivation practices

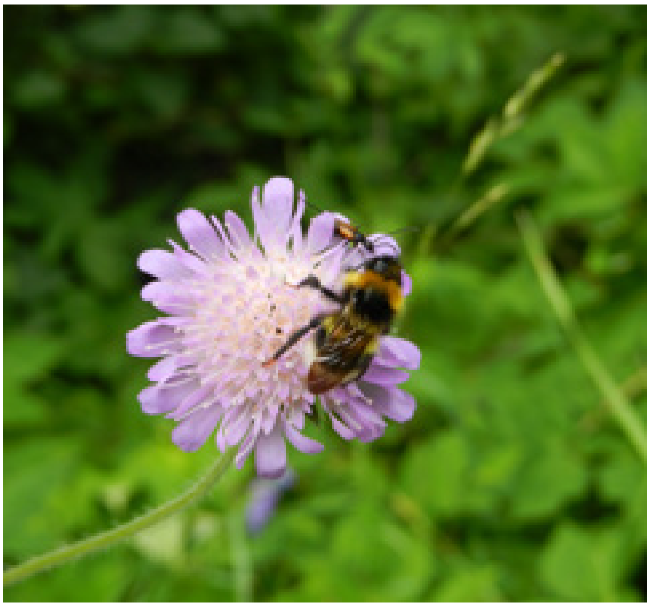
Crofting provides a possibility for pollinator-enhancing farmland. For instance, the last remaining strongholds of two of the most endangered bumblebee species, *Bombus distinguendus* and *B. muscorum*, can be found in areas in western and northern Scotland.[34; 35] Agricultural units there consist of small areas of enclosed lowland grasslands with common grazing. Crofters typically cluster together to implement small-scale arable rotations and livestock production.[3] In the traditional crofting system there is mosaic land use. It is also important to avoid too intensive pasturing, because of its harmful impact on species richness of plants and soil characteristics. It is common for there to be few flowering plants in intensively grazed pastures. The addition of a small area of pollinator-specific wild flowers to the pastureland could have a significant impact on bumblebee populations, with as little as 0.4 hectare of wild flowers having the potential to increase bumblebee densities from an average of zero to five bees per hectare of the croft. Although different bumblebee species have different foraging ranges, the combination of small unit size and the close proximity of the crofts to one another suggests that even a relatively low uptake of this approach would provide accessible patches for bumblebees with both long and short foraging ranges.[3] Therefore, heterogeneous, mosaic, extensively used agricultural landscape assures a greater number of pollinator species, as well as specimens, and a successful pollination service.

meadows with a sparse tree layer on neutral soils (wooded meadow). The mowing usually occurs once or twice per season. Compared to flowering crops the meadows are more essential for wild pollinators, providing food throughout the season. The loss of those areas is an important factor driving bumblebee declines in western Europe.[32]

Ensure vital populations. The small areas suitable for different kinds of wild pollinators work as real conservation areas only if they are in close proximity to each other or to lower quality but still suitable areas. The smaller the population, the more vulnerable it is to local extinctions due to environmental and demographic reasons, randomness, and to low genetic diversity. Small populations can be maintained only if there is sufficient migration between neighbouring areas. For some bumblebee species, for example *Bombus muscorum*, all populations more than 10 km apart are significantly differentiated. In some cases, even 3 km may exceed the dispersal ability.[33]

Establish native bee nesting sites. For instance, bumblebee nests may be found in old mice nests, in holes in the ground made by other animals, etc. Solitary bees are dependent on suitable reeds, straws or cavities in wood to build their nests there.

Provide extra nesting sites for native bees.



Bombus hortorum. © Peeter Veromann.

Bombus terrestris. © Peeter Veromann.

Organic farming

Wild pollinators benefit from organic farming as well as maintenance of grassy field margins and various larger patches of natural (forests, wetlands) or semi-natural (fallows, grasslands, parks, trees, hedgerows) habitats. The positive effect of organic farming on the pollinators' species richness and abundance reflects the main idea of organic farming: farming with minimal impact on the environment. In addition, it is also explained by the smaller field size and more fragmented configuration of agricultural landscape compared with conventional farms, and the restricted use of pesticides, greater number of weeds that provide food for both pollinators and rodents, whose nests may be used by ground-nesting bumblebee species.[33] Furthermore, the growing of leguminous plants is indispensable in organic farming and particularly supports long-tongued bumblebees.

Bee gardens

Pollinators need food supplies throughout the vegetative season. This is usually much longer than the flowering of food crops. Human settlements, for instance, are often surrounded by flower beds, where the plant species are selected according to their varying flowering times. The flowers in pleasure grounds start flowering early in the season, and the various species continue flowering until late autumn. Therefore, rural and suburban gardens can provide unique food sources for bees. Large, colourful flowers and an attractive smell usually signal nectar sources, and pollinators use these signals to find flowers from a distance and learn to look for similar sources.

Bee gardens should contain plants with flowers that are good nectar and pollen producers. Another point to remember is that bees prefer more abundant flowers. Bees learn profitable flower types and then use that knowledge to save time and energy when foraging. Therefore, they often avoid single-standing flowers, because too much energy is wasted learning how to obtain the nectar. Perennial plant species also enhance pollinator fauna near human settlements. The undisturbed soil beneath perennial plants contains cavities which ground-nesting bees use as nesting sites.

The distances between nesting and foraging sites, as well as between individual foraging sites, are important to bees. The foraging range of the honeybee can be 1 to 5 km, depending on food resources present. Bumblebees forage up to 1.5 km from the nest and solitary bees often forage within a range of few hundred metres. Therefore, the landscape may play an important role for bees in using bee gardens as an extra foraging and nesting source.

© Reet Karise.

Nesting habitats of solitary bees

Solitary bees constitute a numerous group. About 70% of solitary bees are soil-nesting species; others are cavity nesters that use plant stems (reeds, straw), abandoned insect borings in old wood, or other suitable holes. Solitary bees need several different habitats for a successful life cycle: one for nesting and another for foraging; some species even need to collect building material.

Soils that provide suitable nesting sites for solitary bees should be bare or sparsely vegetated, sandy, fine-grained, friable and dry, with low humus content. There should be the maximum amount of sunlight and therefore south-facing slopes are preferred by the insects. The sparse vegetation is necessary to maximize exposure to the sun and to prevent plant roots from growing into the bees' brood cells. Excess moisture should be avoided in order to protect stored food provisions and offspring from various fungal infestations.

Cavity nesters often use plant stems and dead wood. The plant stems can easily be substituted by bunches of reed and straw. These artificial nesting communities should be placed in open land and protected from rain. To attract different solitary-bee species the cavities in nest aggregations should have varying diameters, lengths and orientations. Many species have been found in large aggregations in thatched roofs.

Soil fertility

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The importance of soil biodiversity for soil fertility

Maintaining soil fertility is central to the productivity of agricultural land both now and in the future. Soil fertility is the capacity of a soil to support crop production through (1) the availability of different elements required for plant growth; and (2) the uptake of those elements by plant roots when the plants need it.[36] Thus, soil fertility not only depends on the chemical composition of the soil at a certain point in time, but is also the outcome of the relations between chemical, physical and biological soil properties and processes. As such soil fertility is determined by various biotic and abiotic factors that interact with each other (Figure 5). The activities of many different organisms that inhabit the soil are of crucial importance here.

The soil should be seen as a living system, which hosts an enormous diversity and quantity of soil organisms, most of which are invisible to the human eye.* The biodiversity below ground, in terms of the variety of

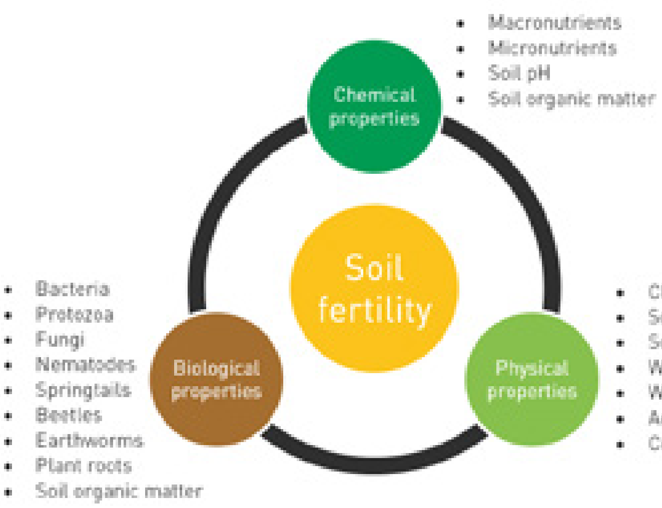

Figure 5: Properties of fertile soil. © Mirjam Pulleman.

* FAO soil biodiversity portal; http://www.fao.org/ag/AGL/agll/soilbiod/

species and numbers of individuals, is many orders of magnitude bigger than that above ground, especially in agricultural systems. More importantly, soils, together with the biota that inhabit them, are absolutely essential in sustaining plant growth, food production and the cycling of carbon, nutrients and water between soils, surface waters and the atmosphere.[37] Human life could not exist without them. The different groups of soil organisms range from microscopic organisms (e.g. bacteria, fungi or protozoans) to soil meso- and macrofauna (e.g. mites, springtails, nematodes and earthworms). Together they form a complex food web in which organisms eat and are eaten (Figure 6). Many organisms also interact with plant roots in different ways. This biodiversity that is hidden below ground is the motor behind the natural processes that regulate soil organic matter decomposition, carbon and nutrient cycling, disease regulation and soil structure formation. Organic matter present in the soil or at the soil surface as living or dead plant material provides the energy, carbon and nutrients that drive most of them. The total amount of soil organisms present in a hectare of agricultural soil depends on soil type, soil pH, organic matter content, climate conditions, crop type and soil management, but can typically range from 2 to 5 tons per hectare, corresponding to up to 10 cows per hectare.

How does it work?

Most of the belowground biomass, besides living plant roots, consists of bacteria, fungi and other microorganisms. They are largely responsible for the process of organic matter decomposition, thereby gradually releasing important plant nutrients like nitrogen and phosphorous. Certain groups of fungi or bacteria form intimate associations with plant roots to their mutual benefit. In this case the fungi or bacteria

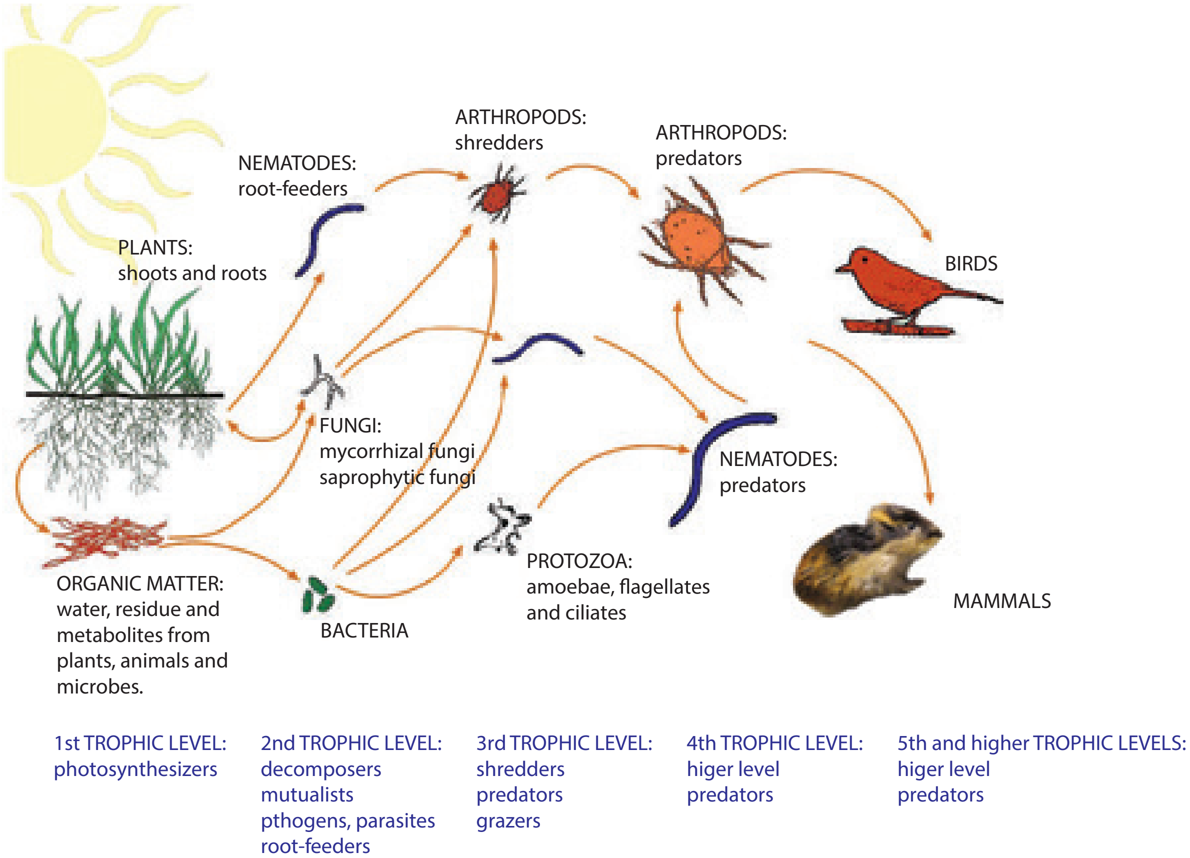

Figure 6: The soil food web. (Source: European Atlas of Soil Biodiversity*)

* http://eusoils.jrc.ec.europa.eu/library/maps/biodiversity_atlas/

fulfil their energy needs by obtaining carbohydrates from the plants. In return the microorganism involved helps the plants to take up phosphorous (e.g. mycorrhizal fungi) from the soil, fix nitrogen from the atmosphere (e.g. bacteria living in symbiosis with the roots of leguminous plants), or by protecting roots from pathogens. The activities of soil microorganisms in general are regulated by different groups of soil fauna which feed on them. Examples include bacteria-feeding or fungi-feeding mites, nematodes or springtails. Other soil animals, for example earthworms, potworms or isopods, fragment plant residues and/or mix them into the soil, which makes them more easily accessible to microbial decomposers.

What makes the relations even more complex is that many organisms contribute to more than one soil process or function at a time. Soil organisms such as earthworms and potworms, for instance, feed on organic matter and mix it with mineral soil. By doing so, they not only affect carbon and nutrient mineralization but also create and modify soil structures.[38] Earthworms are particularly well known for their burrows, which can extend several metres in depth and contribute to water infiltration and soil aeration and are often used by plants to expand their roots. Their excrement forms stable and crumbly soil structures several millimetres in diameter that tend to be enriched in soil organic matter and nutrients. Potworms have a similar role in soil, although they are smaller than the earthworms and as a result their excrement is also smaller.[39] These organisms therefore affect plant growth not only by making nutrients available but also by making them more accessible to plant roots and by keeping the soil aerated and improving drainage of excess water.

All these organisms together modify the soil environment and conditions for plant growth while they, in turn, are strongly affected by the soil environment and therefore by agricultural management practices. Although the majority of the soil organisms fulfil beneficial roles in (agro)ecosystems, a minority of the species that spend all or part of their life stages in soils are notorious for their role as agricultural pests or diseases and may cause significant yield losses. For example, nematodes form a very species-rich group which is mostly beneficial, but also includes a minority of particularly well-known plant parasitic nematode species. Many other soil organisms help to control those pest and diseases in various ways, through predation, parasitism, competition for food or other resources, or by inducing defence mechanisms in plants.

How intensive agriculture limits the benefits provided by soil biodiversity

Biodiversity worldwide is being lost rapidly as a result of many pressures arising from human activities. This is also true for the biodiversity below ground. The expansion, intensification and mechanization of agriculture have been identified as major causes of soil biodiversity decline and soil degradation in Europe. Other, related, threats to biodiversity and to agriculture include soil erosion, soil compaction, soil contamination, soil sealing, salinization and climate change.[40] In intensive agriculture many of the functions provided by the soil biota have been replaced by non-renewable external inputs, which can by themselves have a negative impact on soil biodiversity. For example, ploughing is used to break up soil compaction, to aerate the soil and to control weeds. This comes at a high cost, not only in terms of fossil fuel use. In the process many of the organisms that maintain a good soil structure are lost through mechanical damage, disturbance of their habitat or predation.[41] Synthetic fertilizers have to a large extent replaced the organic matter inputs which are the primary food source for the soil biota, and pesticides are applied to control weeds, pest insects and diseases, but often they also harm beneficial organisms.

The latter is especially the case for broad-spectrum biocides, but the more selective pesticides also have effects on non-target organisms. It is difficult to make generalizations make. The vulnerability of soil biota to pesticides differs strongly between (species) groups in combination with the type of pesticide applied. However, data are available only for a small set of pesticides and very few soil fauna species or species groups. Moreover, immediate lethal effects have been studied more intensively than more long-term effects, e.g. through reduced reproduction.[42] Toxicity and persistence of pesticides in soils after their application are also dependent on soil properties as toxic compounds can be bound to soil minerals or organic matter, dissolved and lost through run-off or drainage, or broken down into harmless compounds by certain soil organisms.[43]

Translating losses of soil biodiversity to changes in soil fertility, crop production and other ecosystem services, however, is not easily done. Relations are complex, and many different species that coexist in the soil can perform similar processes. Therefore, loss of species does not necessarily lead to loss of important processes or functions. The question: '*How many* species do we need to conserve?' is therefore not the right question to ask and is impossible to answer. What is more relevant is: '*Which species* are crucial for maintaining certain functions and *how sensitive* are they to changes in environmental conditions, soil management or climate change?' Of particular interest are keystone species. These are organisms that have a disproportionately large effect on soils due to their unique role in certain soil processes that cannot be performed by other species.[44] Examples are fungal species that are able to decompose certain organic compounds that other organisms cannot degrade,[45] bacteria involved in atmospheric nitrogen fixation or nitrification, or fungi that assist plant roots in the uptake of phosphorous.[46] Earthworms are also keystone species, because of their unique role in soil structure formation.[47]

How different agricultural management practices and crop choices impact on the soil community is only partly understood, as the many interactions between different organisms in soil and their abiotic environment (e.g. soil type and climate) are extremely complex. However, research on this topic is increasing, in both agricultural and natural ecosystems. By building on this scientific knowledge, as well as through on-farm experiments and demonstrations, we can improve management practices to strengthen FAB in soil. Strengthening and safeguarding the provision of ecosystem services from agricultural soils can benefit both farmers and consumers, as well as the surrounding environment.

How can management restore soil biodiversity and soil functions?

Applying FAB-based practices (using the services provided by FAB) in the management of agricultural soils aims to make agricultural production more sustainable by creating the conditions that allow the soil biota to perform important functions, rather than replacing those functions by ever-increasing inputs of agrochemicals and fossil fuels. Such practices are applied with a focus on improving soil structure, water infiltration and soil conservation, and improving nutrient availability and uptake and for enhancing disease suppressiveness of soils (see 'Reaping the benefits of soil biodiversity by reducing soil tillage?' on page 27 and 'Microorganisms and the suppression of soil-borne diseases' on page 28). In practice, the question of which soil functions and target organisms should be stimulated depends largely on local conditions such as climate and soil characteristics, the production objectives (e.g. crop type and farming style) and the main problems that farmers encounter. There is no recipe or principle that fits all. For example, in the Mediterranean region farmers may face problems of drought stress and soil erosion, while in North-West Europe excess water may be a problem.
More information and examples on soil and water conservation, pest control and disease control can also be found in the following sections.

Generally speaking, stimulating biodiversity-based soil functions requires management practices that improve the habitat quality for beneficial organisms. This is often done by applying the following five management principles:

1. Manipulating the quality and amounts of organic matter inputs in the soil.
2. Reducing mechanical soil disturbance, especially ploughing (soil inversion) and compaction by heavy machines.
3. Keeping a continuous green soil cover through the use of cover crops.
4. Crop diversification (crop rotation, intercropping).
5. Reducing harmful synthetic inputs such as pesticides and avoiding biocides.

These principles cannot be considered in isolation, and often a combination of two or more of them is applied in practice. For example, reducing soil tillage (e.g. autumn ploughing) offers possibilities to continue the growth of a cover crop over winter, which increases the amount of organic matter inputs to the soil (combination of 1, 2 and 3). Similarly, crop diversification reduces the need for pesticides (combination of 4 and 5). In reality, there may not always be such a win-win situation and it may be necessary to weigh the positive and negative effects. In non-ploughed soils, the use of herbicides to control weeds may be higher, or certain diseases may become prevalent and require new strategies for disease suppression or control. On the other hand, field data and simulation modelling have demonstrated how a reduction in soil tillage can be important to obtain efficient biological pest control by natural enemies. Studies in north-west France and Finland showed that successful biocontrol of the pollen beetle, an important oilseed rape pest in Europe, depends on a combination of landscape factors. Apart from the presence of natural and semi-natural habitats and pesticide use, the proportion of the previous year's oilseed rape fields with reduced soil tillage or direct seeding played an important role.[48; 49] Less intensive soil tillage reduces the mechanical destruction of the parasitoid pupae, which overwinter in the field soil, and can result in a fourfold increase in parasitoid numbers in the following year. Therefore, applying FAB principles in soil management requires an integrated approach considering the soil as a complex system and considering synergies and trade-offs between different management decisions.

Economic aspects of soil biodiversity

The importance of good soil management is recognized by many farmers, also in economic terms. The condition of the soil not only affects farm income through the impact on crop yields, but also strongly determines the need for, and effectiveness of, external inputs and labour. Moreover, the building up and maintenance of a 'good soil condition' requires a long-term investment. For example, in the case of reduced tillage, up to 5 to 6 years of careful management and investments in machinery and learning may be required before the economic benefits become apparent.[50] Similarly, increasing organic matter levels in soils requires the continued addition of high amounts of plant residues or manure for several years before differences can be detected. On the other hand, a good soil condition can be destroyed from one day to the next, for example, by using heavy farm machinery under too wet conditions or inappropriate tillage practices.[47] So again, a long-term vision for soil management is essential.

The immediate benefits of FAB may be more critical for organic growers than for conventional growers who have the possibility to compensate to some extent for suboptimal soil functioning by using chemical fertilizers or pesticides. However, there are clear indications that increasing scarcity of natural resources (e.g. phosphorous) and high fuel prices, legal restrictions on the use of fertilizers and pesticides, or development of resistance against broadly used pesticides are posing their limitations as well. In fact, many farmers report that one of the reasons for applying reduced tillage farming is reduction in fuel costs.[50] Due to higher costs and stricter limitations on fertilizer use, there is also a need for management practices that increase nitrogen use efficiency in the soil-crop systems. Therefore, current and future price developments of external farm inputs, as well as agricultural policies, will have a strong effect on the economic feasibility of FAB-based practices and the urgency felt by farmers and the wider society to invest in soil biodiversity conservation. Novel technologies, such as GPS-driven farm operations and different types of soil or crop sensors, commonly known as **precision agriculture**, offer scope for improvements in the management of soil and soil biodiversity management as well. Other examples include the use of fixed traffic lanes to reduce soil compaction or crop diversification for biological pest control.

Benefits at and beyond the farm level

Increasing functional soil biodiversity on farms not only creates benefits at the farm level, but will also have an important spin-off to the surrounding environment. Such benefits include control of soil erosion that may damage public infrastructure and water quality and often poses high costs to society. It can also contribute to reduced fertilizer and pesticide losses to the environment, and reduction of greenhouse gas emissions through lower use of fossil fuels and sequestration of atmospheric CO_2 in soil organic matter.

Conversely, interactions with the surrounding landscape can also have an effect on the soil biodiversity at the farm level. For example, mouldboard ploughing is known to have a detrimental effect on populations of certain earthworm species, especially those that make deep, permanent burrows in the soil that facilitate water infiltration. It has been reported that these earthworm species recolonize arable soils upon conversion to reduced tillage systems without soil inversion.[51; 52] However, it can take several years before populations have been restored. The rate of recolonization probably depends on the presence of semi-natural habitats, permanent grasslands or relatively undisturbed field margins in the surrounding landscape in which those earthworm species have been conserved.[53] More research is currently under way to investigate landscape-level effects on soil biodiversity in farm fields, and to better understand the interactions between biodiversity above ground and below ground. This will help to show what synergies can be created by managing agricultural fields and adjacent field margins or semi-natural habitat to stimulate biodiversity above ground and below ground in order to support a range of ecosystem services.

Reaping the benefits of soil biodiversity by reducing soil tillage?

There is increasing interest among growers in Europe to explore the benefits of reduced tillage systems.[50; 54] Among advantages such as cost reductions, moisture conservation or erosion control, reduced tillage can help to stimulate soil biodiversity. It has long been known that conventional ploughing disrupts the soil food web, whereby soil animals with larger body sizes and slow reproduction times are the first ones to disappear.[41] These animals play an important role in incorporating organic matter into the soil and in the formation of soil structure, such as aggregates and burrows. They thereby modify the hydrological properties of the soil and also impact on other, smaller, organisms.[55] Getting rid of the plough can therefore result in beneficial effects on the soil structure and on nutrient dynamics, provided that there is enough organic matter as a food source for the soil biota.

In reality, however, a variety of reduced tillage systems are practised under a wide range of climates, soil types and crop rotation across Europe. Reduced tillage systems range from more or less superficial ploughing, to non-inversion tillage to direct seeding, using different types of machinery and implements. Tillage intensity also varies depending on crop type, where more intensive tillage may be required for certain crops in the rotation (e.g. root crops require more intensive tillage than cereals). The impact of different forms of reduced tillage on soil biodiversity has been poorly documented, while more work is required to understand the subsequent effects on crop production. Moreover, there is a need to predict the effects of changes in soil biodiversity in the short as well as the longer term. In other words, how much time does it take before the benefits can be reaped?

The SUSTAIN project* aims to answer these questions. Researchers in the Netherlands and France have joined forces to quantify and compare the effects of different tillage practices on soil biodiversity in France (Brittany) and the Netherlands. The regions have in common that they have a cool, wet climate with high risk of excess water, hence the importance of maintaining good water infiltration. Research is being performed in long-term field experiments lasting from 3 to 12 years, where tillage systems, such as conventional ploughing, non-inversion tillage, superficial tillage and direct seeding, are compared. This is done in conventional and organic crop rotations including root crops such as potatoes and sugar beets. Effects on earthworm species and nematode families are monitored for several years and important ecosystem functions and services are measured, such as soil structure formation, soil stability or erosion control, water infiltration, soil organic matter and nutrient retention, and crop production. Nematodes are a highly diverse group representing bacteria feeders, fungal feeders, carnivores (important for biocontrol) and plant feeders (plant pathogenic nematodes). Changes in the relative importance of each of these groups are a useful indicator of soil quality.[56] Different earthworm species also have different effects on soil functions. The deep-burrowing (or anecic) species are important for the formation of vertical macropores that improve water infiltration. The soil dwellers (or endogeics) are important for aeration of the top 20 cm of the soil and form stable aggregates. The litter dwellers (epigeics) live at the soil surface and are important for decomposition of fresh organic matter and nutrient mineralization. Results so far have shown that reduced tillage systems do not necessarily increase total earthworm numbers, but do result in better conditions for deep-burrowing and litter-dwelling earthworms. Soil-dwelling earthworms, on the other hand, were highly dominant in conventionally ploughed soil. Earlier studies have shown that macropores created by earthworms can support water infiltration and root growth. As they are lined with organic matter they can retain agrochemicals.[57]

* http://www.snowmannetwork.com/main.asp?id=110

Microorganisms and the suppression of soil-borne diseases

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It has been shown that soil (micro)organisms are a key factor in the suppression of soil-borne diseases.[58;59;60;61;62] The mechanisms involved include competition for nutrients and space, the excretion of substances that are harmful to other organisms (antibiosis), the parasitizing of another parasite (hyperparasitism) and the induction of plant disease resistance.[63;64;65] Some studies have demonstrated that soil microorganisms may also reduce the development of air-borne, leaf diseases.[66] Here, beneficial microorganisms and plant pathogens are physically separated, and induced systemic resistance (ISR) has been identified as the main underlying mechanism. Fliessbach *et al.* and Tamm *et al.*[67–68;69] evaluated the long- and short-term effects of organic fertilizer inputs on physical, chemical and biological soil properties as part of the long-term DOK trial* in Therwil (Switzerland), and of short-term fertilizer input experiments with lettuce in Bonn (Germany) and onions in Yorkshire (UK). Soils from the DOK long-term trial and from the three short-term fertilizer input trials were also evaluated for differences in suppressiveness to soil- and air-borne diseases using the bioassay systems basil (*Ocimum basilicum) – Rhizoctonia solani*, cress (*Lepidium sativum*) – *Pythium ultimum*, *Arabidopsis thaliana* – *Hyaloperonospora parasitica* and tomato (*Solanum lycopersicum*) – *Phytophthora infestans*.[69] It was found that soil type is a key determinant for suppressiveness to diseases. Soil from the Yorkshire site showed the highest level of suppressiveness to all tested diseases, a result that was confirmed by soil samples taken in the subsequent year and evaluated in two bioassays.[69; 70] Furthermore, it was shown that site-specific suppressiveness can be modulated by long-term soil management and, to a lesser extent, by short-term fertilizer inputs.[69] For instance, within the DOK trial, *A. thaliana* plants growing on the least suppressive soil showed around 30% more disease incidence than plants growing on the most suppressive soil. In contrast, short-term fertilizer input treatments had little effect on the suppressiveness of soils to the three pathogens included in the study.[69] Exceptions were (1) a significant reduction of disease caused by *H. parasitica* in *A. thaliana* grown in soils amended with composted farmyard manure when compared with chicken manure in soil samples from the Yorkshire site, and (2) a significant weight reduction in *O. basilicum* infected with *R. solani* in soils amended with farmyard manure compared with soils amended with inorganic fertilizer in soil samples from Bonn.

The systematic use of soil fertility management techniques to reduce diseases is an intriguing concept in theory, but is not yet widely used in practice, partly because the underlying principles are not understood. Site-specific factors, which cannot be influenced by agronomic practices, have a greater impact than cultivation-specific effects within the same site. Nevertheless, short-term, and in particular long-term, management strategies have been shown to have the potential to influence the suppressiveness of soils to certain diseases.

A follow-up study examined the role of soil microbes in disease suppressivity, and the potentials and

* http://www.fibl.org/en/switzerland.html

limitations in restoring soil suppressiveness to soil-borne and air-borne diseases in disturbed soils.[70] For example, addition of the soil-borne pathogen *Pythium ultimum* to sterilized soil resulted in much higher damage to test plants than when the same pathogen was added to native soil, demonstrating that suppressiveness is dependent on living soil microorganisms. Re-inoculation of sterilized ('dead') soils with small amounts of native soil restored suppressiveness to some extent, but not completely. None of the native microbial populations (as defined by microbial biomass, activity and community structure) could be fully restored in the soils under study within the relatively short period of observation. These data demonstrate that sterilization of soils can enhance the susceptibility of plants to soil- and air-borne diseases and suggest that this soil degradation process may be at least partially irreversible. Therefore, deleterious agricultural soil management practices, such as soil fumigation or heat treatments of soils, frequently used in vegetable cropping, should be avoided.

Natural pest control

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The importance of natural pest control as an ecosystem service*

Crop pests constitute a serious threat to crop production and have done so since recorded history. Insect pests can cause severe crop losses both on the field (pre-harvest) and during crop storage (post-harvest). It is estimated that approximately a third of crop production is lost to pests, diseases and weeds.

In agriculture, pest species find themselves in a land of plenty where there is an overabundance of food plants and enemies are few. In natural ecosystems, on the other hand, plant-feeding insects (known as pest species in agricultural crops) usually do little damage. This is to a large extent due to the fact that natural habitats tend to be teeming with insect predators and parasitoids that attack plant feeders, keep their numbers in check and thereby protect plants from serious damage.

This shows that natural pest control is an important ecosystem service that can also be employed to help protect crops. Biological control makes an important contribution to controlling pests and diseases in agriculture, forestry and greenhouse horticulture worldwide. This ecosystem service is estimated to represent an economic value of €320 billion/year globally, more than triple the value of pollination.[71; 72]

To what extent does modern, intensified agriculture affect ecosystem service delivery?

In spite of increasing intensification of pest control in recent decades, on-field crop losses due to pests, diseases and weeds increased from 35% to 42% in the period from 1965 to 1990.[73; 74] The continuing problems farmers face in terms of crop protection can be attributed to several factors. One of these is the fact that the use of non-selective agrochemicals undermines natural crop protection mechanisms by eliminating beneficial organisms responsible for natural pest and disease control. The impact of beneficial organisms responsible for biological control is also severely constrained by land-use change. In the increasingly intensified agricultural landscape beneficial insect groups and the services they provide have declined as a result of the rapid depletion of semi-natural habitat and non-crop vegetation.[75; 76] A broad range of biological control agents depends on these semi-natural habitats for shelter, overwintering and as a source of nectar and pollen.[77] Recent studies have provided clear evidence that natural enemies are indeed starving in the absence of flowering vegetation[78; 79] and that this has dramatic consequences for natural pest control.[80]

* Note: This discussion deals with insect/invertebrate pests. It does not cover mammal and bird pests or other groups that may be suppressed by predators or by increasing hedgerows, treelines, forests, etc.

A hoverfly (*Episyrphus balteatus*) on a buckwheat flower.

How can landscape management support natural pest control?

Insect predators that naturally occur in agricultural systems can be preserved and enhanced with simple cultural techniques. Such practices may involve provisioning natural enemies with resources that are lacking within the agricultural crop, such as nectar, pollen, alternative prey, or shelter (overwintering sites).

Adding floral resources can be a simple and effective tool to support predators and parasitoids and to harness the biocontrol services they provide. Using field cages with plots of cabbage plants with or without the addition of a flowering buckwheat plant, Winkler *et al.*[80] showed that the majority of *Diadegma semiclausum* (a parasitic wasp) failed to attack any Diamondback moth (*Plutella xylostella*) larvae in the cages without nectar plants, whereas individuals provided with a nectar plant parasitized more than 300 larvae each. Thus, adding food sources to agro-ecosystems could be a simple and effective way to enhance the effectiveness of biological control programmes.

The realization that flowering vegetation can be a powerful tool to support pollination and biological pest control has given rise to an increasing offering of commercial seed mixtures. Several countries provide sizeable subsidies for the use of such seed mixtures in field borders, non-crop areas or undergrowth. Despite the substantial investments in these programmes, there is often surprisingly little information available with regard to the actual suitability of the included plants as food sources for the target insects[81] or the ultimate impact of flowering plants on biological control.[82]

How to optimize pest control through targeted use of biodiversity in landscape management

The creation of wildflower strips and management of other non-crop vegetation has emerged as a key tool to support beneficial insect groups and the services they deliver. Yet the efficacy of landscape management programmes in terms of delivering ecosystem services is often limited by an incomplete understanding of the resource requirements of beneficial insects and how best to provide these resources.

The choice of field margin compositions for the support of natural pest control has long been done more or less arbitrarily.[83] These 'shotgun approaches' have been hit-and-miss in terms of their delivery of ecosystem services. An uninformed choice of non-crop vegetation

A parasitic wasp on *Apiaceae*.© Felix Wäckers.

not only means missing out on potential benefits but may also actually generate negative effects. Arbitrarily composed floral vegetation can increase pest populations,[84; 85] support enemies of beneficial insects,[86] and cause weed or disease problems.

However, these problems can be avoided by taking a *targeted approach* in the choice of flowering plants for field margins or other types of non-crop vegetation. This targeted approach is based on the simple concept that different insect groups exploit different flowering plants. By selecting those plants that are especially suitable for the insects delivering pest control, while excluding plants that are preferred by nectar/pollen-feeding pests, the positive impact of flowering landscape elements can be maximized.[87] On the basis of recent extensive work it is now possible to provide farmers with accurate prescriptions for seed mixes and landscape management that specifically target and optimize pest control benefits, while minimizing possible negative effects. As an alternative to the 'hit-and-miss' approach, this 'targeted approach' is based on three key steps: (1) quantify the nectar or pollen bottleneck (level of food limitation of insect predators and parasitoids) under field conditions; (2) informed selection of flowering plants that can be successfully exploited by the target beneficiaries; (3) provide the flowering plants at times and in locations that optimize their exploitation by the predators delivering natural pest control services.

The use of this targeted selection of flowering plants has been shown to generate significant benefits to natural pest control in a number of large-scale projects worldwide (e.g. the Ecostac project*). This approach helps enhance natural populations of insect predators or parasitoids (known as 'conservation biological control'). Suitable flowering plants also improve the efficacy when releasing commercially available biocontrol organisms (augmentative biological control). In the latter case, the flowering vegetation will not only help feed the released insects, it will also help retain them in the area of release.

By supporting the beneficial insects that deliver pest control services through targeted landscape management, the need for chemical intervention can be drastically reduced. This means less mortality of the naturally occurring predators and pollinators, thus generating a positive feedback loop in terms of both pest control and pollination.

* Ecostac: Optimising ECOsystem Services in Terms of Agronomy and Conservation; www.ecostac.co.uk

Pick and mix

There is an urgent need among policymakers setting agri-environment scheme prescriptions and practitioners managing the agricultural landscape for practical advice on targeted seed mixes and management of non-crop elements for ecosystem service delivery.

Growers are more likely to implement flowering field margin options (e.g. in Stewardship Schemes) if these margins are specifically developed to provide optimal and multiple benefits in support of sustainable production. Growers also look for prescriptions that fit with their individual cropping regimes, soil/climate conditions and management needs.

To be able to provide such a tailored approach, researchers in the Netherlands and the UK have compiled a unique, comprehensive database bringing together widely scattered information on more than 100 plant species, rating them on the basis of 14 criteria. These criteria include issues relating to their suitability in supporting predators and parasitoids as well as important groups of pollinators. In addition to criteria describing the impact of a flowering plant on beneficial insect groups, information was included on flowering time, plant growth type, the plant's native range, climate and soil requirements and seed cost, as well as potential negative effects (e.g. potential weed issues and whether plants can act as potential reservoirs for pests or crop diseases). This database provides a unique tool allowing informed design of site and crop-specific non-crop elements that optimize pest control and pollination services.

FAB field margin. © Paul van de Sande.

A teasel flower with ladybeetle eggs. © Felix Wäckers.

Evidence that informed selection of flowering plants pays off in terms of pest control*

There are various ways to measure whether flowering field margins have the intended impact on insect predators and the pest control service they provide. In a number of large-scale projects in the Netherlands and the UK, crops with flowering field margins were compared with control fields bordered by grassy margins, and it was demonstrated that:

- flowering field margins provide superior overwintering sites for many biocontrol organisms;
- biocontrol organisms actually benefit from visiting flowering plants by refuelling their energy supplies through feeding on nectar and pollen. Energy reserves can be shown to be three times higher near the flowering field margin;
- flowering field margins harbour many more insect predators and parasitoids than the grassy margins. These numbers effectively spill over into the crop, where clearly elevated levels of pests' natural enemies are seen up to 30-50 metres away from the flowering field margins;
- crop pests suffer more attacks from the larger contingents of predators and parasitoids;
- significant reductions in crop damage and actual increases in yield are achieved.

However, studies also emphasize that it is important to choose the right flowering plants. For example, when flowers preferred by cabbage pests were planted next to a field of Brussels sprouts, the crop suffered higher damage from Cabbage white caterpillars.[88] This problem was prevented by excluding the floral culprits from the flower seed mix.

The strongest positive impact can be expected in crops and landscapes that are depleted of nectar and pollen sources. Flowering weeds are usually not suited to feed insect predators, as the majority of agricultural weeds are wind pollinated or have otherwise unsuitable flowers.

* See also http://www.ecostac.co.uk

The benefits of being close

An important question to consider is where best to place the flowering vegetation relative to the crop. As a rule, the closer the nectar and pollen are to the actual crop, the more benefits are generated in terms of improved pest control. This is due to the fact that in order for predators and parasitoids to benefit, they will have to move between the nectar/ pollen source and the pests. In the case of flowering field margins, one typically sees a declining impact of flowering margins over a distance of 30-50 metres. This obviously also depends on the predator species. While some predators, such as hoverflies, are quite mobile, others are rather limited in their mobility.

One way to bring the floral food closer to the crop is to grow the flowering plants in strips within the crop. This may not be feasible in all crops, but in the case of orchards or vineyards there is room between the rows which can easily be used to grow flowering herbs in the understorey. In other cases rows used for tractors or other equipment can provide places to provide nectar and pollen.

To get closer still, one can grow 'flowering companion plants' alongside individual crop plants. This is especially effective in crops such as cabbages that are planted in plugs, rather than sown. In these instances, the companion plant can be grown together with the crop plant in the nursery. If companion plants are selected not to compete with the crop for water, light and nutrients, as well as for providing suitable nectar, this can be highly effective.

The best option, of course, is to provide the necessary food directly on the crop plant itself. Evolution has actually come up with this best solution.

A number of plants actually provide sugars through extrafloral nectaries (nectar-secreting plant glands that develop outside of flowers) for the simple purpose of attracting sugar-dependent predators as bodyguards. When these return the favour by attacking pests, both parties benefit. To ensure that nectar production and pest presence are really linked in space and time, plants often produce this nectar from those leaves that are being attacked by the pest. Extrafloral nectaries are also found on the leaves and stems of a number of crop plants, including broad beans, zucchini, cherries, plums and cotton. In these cases, varieties that produce more or better quality nectar can be selected. For crops that do not produce the nectar themselves, a similar effect can be achieved by applying low levels of sugar sprays or by dusting with selected pollen.

Lacewing larva feeding on cotton extrafloral nectar.
© Felix Wäckers.

Disease Control

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FAB for disease control

Overall, yield and quality losses due to diseases vary greatly depending on the crop, the region, and the growing system. Under European conditions potatoes in particular are subject to many fungal, bacterial and viral diseases. The most notorious is potato late blight which can cause huge losses where the climatic conditions are humid. Cereals can suffer from rusts and mildews and from soil-borne pathogens such as take-all and eyespot where rotations are too tight. Legumes suffer a lot from soil-borne diseases which often go unseen and many growers are not aware how much the nitrogen fixation of legumes is reduced by root diseases.

Diseases can be favoured by many growing practices such as too high or imbalanced nutrient inputs, the choice of susceptible crop cultivars, and practices that cause damage to crops. Thus, crops that receive high nutrient inputs generally grow more densely, creating a microclimate that may favour fungal and bacterial pathogens and attract aphids that transmit viruses to the darker green foliage. Crops that receive high levels of nitrogen often are more susceptible to disease than crops grown under moderate nutrient inputs. Thus, cereals usually are more prone to attacks by powdery mildew and rusts under conventional rather than under organic growing conditions, due to the higher nitrogen

Rapeseed fields. © Maria Finckh.

Flowering cover crop. © Maria Finckh.

inputs in conventional systems. On the other hand, crops suffering from low nutrient supply may lack the energy needed for adequate resistance response.

In addition to these factors, a lack of biodiversity in agriculture at several scales has long been recognized as a key element that contributes to the vulnerability of crops to diseases. On the one hand, there are fewer and fewer crops grown and fewer and fewer native plants and field margins are left standing. On the other hand, the crops that are grown are genetically very uniform. Typically, all plants in a wheat field are genetically identical and even different wheat varieties often share part of their ancestors in the breeding process and are thus genetically very similar to each other.

Problems in disease control due to a lack of biodiversity

It is estimated that during the last century 75% of crop diversity overall was lost.[89] Breeding for genetic uniformity, increased field sizes, mechanization of field operations and industrialization of food processing have all contributed to this dramatic loss of plant genetic diversity in agriculture. Pesticide and fertilizer use

Diverse field margin. © Maria Finckh.

have also contributed by allowing for the production of susceptible crops, shortening or abandoning rotations and reducing the diversity of non-agricultural plant and animal species (native plants, natural enemies, microorganisms and aquatic species). Currently, about 70% of the fields in Germany are grown to maize, winter wheat, winter barley and rapeseed. In addition, the few crop species that are being grown widely are usually genetically uniform within fields and a few varieties dominate the market.

The main reasons why this development increases disease problems and thus the use of pesticides are:

1. Lack of or too short rotations: Soil-borne pathogens depend on the presence of their host plants for survival. The tendency in modern agriculture to use fewer and fewer crop plants has led to very short breaks between crops and to an increase in field size. For example, in intensive potato production, potatoes are often grown every three years. Maize is often grown four out of five years or more and cereals typically dominate rotations, accounting for 60-80%. Even if different crops are grown in successive years, they are often susceptible to the same pathogens. For instance, barley and wheat share pathogens such as eyespot and take-all. In addition, certain weeds such as quackgrass (*Elymus repens)* also

Sclerotinia on oilseed rape. © Maria Finckh.

share these pathogens. Thus, not only the crops but also the weeds need to be considered. Wheat, maize, and peas share some of the mycotoxin-producing *Fusarium* species (filamentous fungi), especially *Fusarium avenaceum* and *Fusarium graminearum*. Many legumes share pathogens and often need to be separated by more than four years in order to produce a healthy crop.

2. Strong selective pressure for virulent pathogens: Pathogens in general have the ability to adapt to their host plants in response to selective forces. The larger the area in which a certain resistance is being made use of, the larger will be the selective pressure on the pathogen to develop virulence to this resistance, causing a stronger ability to cause disease. Once the virulence has developed, the previously resistant crop will become subject to large disease epidemics unless pesticides are applied or a new resistant variety is bred.

3. Inability of crops to adapt to changing pathogen populations: Because modern crop plants are genetically very uniform, they have only little potential to adapt to their pathogens through natural selection. Thus, besides increasing the need for pesticides, genetic uniformity also creates the necessity for costly breeding programmes and overall makes farmers dependent on inputs of seeds and chemicals.

FAB-related solutions

The main factors that make agricultural systems more vulnerable to pests and diseases than natural ecosystems are large field size, genetic uniformity within fields and regions and, over years, the use of introduced species, and the cultivation of species under conditions in which they would usually not survive. From the point of view of a pathogen, especially if it is spread by wind, uniform plant stands are ideal. There are a number of mechanisms by which increasing the number of species and varieties grown in a rotation within and among fields contributes to disease control (see 'Effects of biodiversity on diseases and other beneficial effects' on page 43).

Solutions available for biodiversity enhancement in agriculture

Diversity in time is achieved by crop rotation and the addition of cover crops in the off-season. Methods to diversify in space are to grow more species on a farm, to reduce field sizes and to add flowering field margins or hedgerows, to intercrop different species or to grow mixtures of varieties possessing different resistances. An innovative approach is to grow diverse crop populations that are allowed to adapt to their environment over time (see 'Providing diversity that allows crops to adapt: evolutionary breeding' on page 44).

Fusarium white-head on wheat. © Maria Finckh.

Take-all on wheat. © Maria Finckh.

Rotations are the main means to control soil-borne pathogens. Soil- and residue-borne pathogens are usually destroyed by natural decomposition processes and many die if no host is present for some time (in many cases between 2 and 8 years). Rotations have therefore been the mainstay of plant protection in the past. For example, until the late 1990s there was no fungicide registered to fight *Sclerotinia* white mould in oilseed rape because it was known that if rotated properly (four-year break) this pathogen will not pose serious problems. However, the cropping frequency became higher and higher, and nowadays it is common practice to spray against this disease. In Canada, problems with black leg on oilseed rape (caused by the fungus *Phoma lingam*) became so severe that in the 1990s rotations were prescribed to the farmers by law.

Rotations are usually sufficient to protect cereals from foot diseases such as eyespot, *Fusarium* and take-all.

Even pathogens that can survive for very long time in the soil (e.g. some pea root pathogens) are usually reduced by rotations, as the biological activity and thus decomposition processes are sped up. It is important to adapt the rotations to the soil management practice. When ploughing or deep tillage are performed, infected straw often comes back to the surface in the second year; thus, growing a crop with the same susceptibility will require more than a two-year rotation. With reduced or no tillage, after a transition period the earthworm and microbial activity increases and will usually speed up the decomposition of crop residues. Besides improving soil structure, earthworms can directly reduce soil-borne pathogens by eating them and bringing them into contact with microorganisms antagonistic to the pathogens. This often results in reduced disease.[90; 91] The increased organic matter content in the topsoil will also increase overall microbial diversity and the potential of soils to suppress diseases. These effects are site specific and regular checks should be performed (spade test) to verify that the soils have good earthworm activity, which is indicative of good soil conditions.

Reduced field sizes and interrupting with different species and hedgerows generally reduce disease pressure, as the amount of spores produced in smaller fields is reduced and spores are lost while travelling to the next susceptible field. This has also been shown for potatoes.[92] Hedgerows may function as windbreaks, but increased shade in the mornings may mean that leaves stay wetter for longer, thus helping some pathogens to develop. Therefore, it makes sense to manage the hedges for height and to keep a certain distance to the fields.

Spade test of soil. © Maria Finckh.

Growing more marketable species on a farm is sometimes difficult for cereal growers due to a lack of equipment. This can sometimes be solved by cooperating with other farmers specialized in other crops (e.g. by inviting potato and vegetable farmers to enter their crops into a joint rotation).

Adding cover crops such as brassicas, legumes, or other flowering plants in the off-season usually increases organic matter in the soil, providing additional food for earthworms and microorganisms. Additional benefits are soil protection, weed suppression, and the provision of urgently needed pollen and nectar for pollinators. Some cover crops (e.g. some mustards, borages, vetch, and tagetes) are known to directly affect certain pathogens and weeds. However, these effects are not so easy to show in most cases. Cover crops are often also useful for high-value compost production or may be of use for biogas.

Species mixtures are common for cereals with grain legumes. In particular, barley with peas (semi-leafless types) and rye with winter peas can be very attractive. The peas are provided with support and at the same time help to shade out weeds. The harvested crops can easily be separated mechanically or may be used directly as animal feed. Mixtures of wheat with faba beans are also used by some growers, but these are still less common. Rust and mildew in cereals are generally reduced in such mixtures mainly through barrier effects.

Undersowings of low-growing legumes such as white or subterranean clover can be of direct benefit to a cereal by providing biologically fixed nitrogen and by suppressing weeds. Many foot and foliar diseases are dispersed by water splashing. The foliage of intercrops and undersowings reduces rain splash and has been shown to reduce dispersal from plant to plant and upwards within the canopy through barrier effects.[93] Whether undersowings can be used, and at what density and timing, depends on the local climatic conditions and water availability.

Variety mixtures of cereals have been extremely successful in controlling rust and powdery mildew (see 'How do cultivar mixtures work?' on page 46).

Winter pea and rye mix. © Maria Finckh.

For example, in the former German Democratic Republic the use of fungicides against barley powdery mildew was reduced by over 80% by the coordinated use of cultivar mixtures. Cereal variety mixtures and sometimes also species mixtures are officially recommended in Denmark, the UK, Switzerland, and several states of the USA and they are very popular in Poland.[94] In the organic sector, they are generally recommended.

Avoiding potential negative effects of diversity on diseases

Intercropping and species mixtures may lead to higher overall humidity in a plant canopy. This can favour infection by certain pathogens. Thus, plant density needs to be controlled judiciously. This also applies to questions of harvesting. Often, strips are easier to handle and pose fewer problems if two crops react differently to the climate with respect to maturation. Also, when strips or alternating rows are planted, variation in plant height will lead to better aeration and reduce the potential for ear infections in cereals.

When planning rotations that include cover crops, one should carefully check whether the cover crops share pathogens with the planned main crop (e.g. brassica cover crops share diseases such as club root with oilseed rape, leguminous cover crops may share pathogens with peas or faba beans, among others).

Some generalist plant parasitic nematodes thrive where green plants are always available. However, if microbial activity is high, the nematodes are kept in check by antagonistic fungi and bacteria. Including nematode antagonistic plants such as tagetes and members of the borage family can also help reduce the problem.

Effects of biodiversity on diseases and other beneficial effects

Disease reduction in rotations
• Starvation of soil-borne pathogens over time
• Increase of microbial and faunal diversity contributes to reduction of pathogens in soil and residues
Disease reduction in cultivar and species mixtures
• Increased distance between susceptible plants
• Barrier effects of resistant plants growing between susceptible plants
• Induced systemic resistance through avirulent pathogens and other mechanisms
• Microbes on the plant or root surface or inside plants (mycorrhizae, endophytes, etc.) may be enhanced and in turn protect plants from pathogen attack
Other beneficial effects
• Compensation for yield losses by fewer affected hosts
• Reduction of bare soil and layering of crops: - better competition with weeds - better soil and water conservation
• Variation in tillage needs in rotations may disturb weeds
• Yield enhancement through niche differentiation of hosts
• Provision of nectar and pollen for beneficial insects: increased biocontrol and pollination
Possible unwanted interactions
• Pathogens may adapt to several hosts (super races)
• Microclimatic effects may enhance certain problems
• Greater difficulty in reducing weeds mechanically (or with herbicides in conventional systems) • Possible negative effects of weeds: - weeds may serve as alternate hosts for pathogens and insect pests - interactions among virus vectors and weeds

Economic aspects

The economics of diversity very much depend on the timescale considered. Often, in the short term it appears that the measures proposed are costly or, worse, that positive effects take time to show. Thus, seeds for cover crops are expensive and it takes several years for measures to improve soil structure and feed earthworms and result in visible benefits (see section on soil fertility for details), and there are sometimes negative effects in the short term. Nevertheless, softer soils with better structure will require less energy for tillage, and soils with a good structure will suffer less from climatic extremes. Variety mixtures of cereals are commonly grown in many areas of the world, as they generally reduce the need for pesticide inputs tremendously and improve product quality. Problems selling mixtures will depend on the market. Although millers routinely mix different wheat varieties to obtain the right flour quality, they often claim that mixtures are of lower quality. However, there is no evidence to support this claim.

A higher diversity of crops on a farm generally means a more evenly distributed labour requirement and lower risk of total failure, following the principle of not putting all your eggs in one basket.

Providing diversity that allows crops to adapt: evolutionary breeding

This method has been used in the USA since the 1910s. Recently, researchers have been working on it with wheat in many European countries and in the USA.[95] Instead of mixing pure lines or finished varieties, multiple crosses (often called composite crosses) are made among varieties possessing properties of interest (e.g. variation in resistance to diseases and environmental stress, good baking quality). The progeny of the composite crosses is then left to adapt to local conditions. Foliar diseases in such populations are generally low and diversity is maintained even in inbreeding crops such as wheat over many generations.[96; 97] This approach is especially amenable to the participation of farmers in the process of selection and breeding and would allow for on-farm development and maintenance of genetic resources. However, problems still exist with respect to adequate seed health and especially legal questions. Therefore, evolutionary breeding is still restricted to research and is not widely available in practice.

Disease in wheat pure stand. © Maria Finckh.

Disease in wheat population. © Maria Finckh.

How do cultivar mixtures work?

Rusts and mildews are fungi that spread with spores that travel with the wind. In addition, the pathogens produce different races which are specialized to attack only certain varieties. For example, race *a* can attack only wheat variety *A*, race *b* only wheat variety *B*. Once a field planted to variety *A* has been infected with race *a*, all plants can be infected with the spores produced in the field (see figure, left). If, however, variety *A* and *B* are mixed together in the field, race *a* can only attack half of the plants in the field. Variety *B* in between the *A* plants will serve as a barrier to the spread of the spores, just as variety *A* will serve as a barrier to spores of race *b* which may be present on variety *B* (see figure, right). Farmers all over the world make use of these effects by growing cultivar mixtures.

Cultivar mixtures.

Glossary

abiotic factor Physical, chemical and other non-living environmental factors. They are essential for living plants and animals of an ecosystem, providing the essential elements and nutrients that are necessary for growth. The abiotic elements also include the climatic and pedologic components of the ecosystem.

agrobiodiversity The variability among living organisms associated with the cultivation of crops and rearing of animals, and the ecological complexes of which those species are part; this includes diversity within and between species, and of ecosystems.

ancestor An organism from which later individuals or species have evolved.

antibiosis An association between two or more organisms that is detrimental to at least one of them.

bioassay A method of determining the concentration, activity, or effect of a change to substance by testing its effect on a living organism and comparing this with the activity of an agreed standard.

biodiversity The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

biological control Pest control strategy making use of living natural enemies, antagonists or competitors and other self-replicating biotic entities.

biological control agent A natural enemy, antagonist or competitor, and other self-replicating biotic entity used for pest control.

biological pest control Any living organism applied to or introduced into the environment that is intended to function as a pesticide against another organism declared to be a pest.

biota All of the organisms, including animals, plants, fungi and microorganisms, found in a given area.

biotic factor The influence upon the environment of organisms owing to the presence and activities of other organisms, as distinct from a physical, abiotic, environmental factor.

breed A grouping of animals of the same species having a common ancestor and the same set of characteristics. Farmers use selective mating to produce offspring (a breed) with the desired characteristics.

carbon sequestration The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon.

climate change Any change in climate over time, whether due to natural variability or as a result of human activity. (The UN Framework Convention on Climate Change defines climate change as 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.')

compensation Equivalent in money for a loss sustained; equivalent given for property taken or for an injury done to another; recompense or reward for some loss, injury or service.

conservation status The sum of the influences acting on a natural habitat and its typical species that may affect its long-term natural distribution, structure and functions as well as the long-term survival of its typical species or the sum of the influences acting on the species concerned that may affect the long-term distribution and abundance of its populations.

conservation tillage A tillage system that creates a suitable soil environment for growing a crop and that conserves soil, water and energy resources mainly through the reduction in the intensity of tillage, and retention of plant residues.

cover crop A temporary vegetative cover that is grown to provide protection for the soil and the establishment of plants, particularly those which are slow growing. Some cover crops are introduced by undersowing and in due course provide permanent vegetative cover to stabilize the area concerned. The term can include an intermediate crop that can be removed by the use of selective herbicides.

crofting A social system in which small-scale food production plays a defining role. Crofting is characterized by its common working communities, or 'townships'. Individual crofts are typically established on 2–5 hectares of 'in-bye' for better quality forage, arable and vegetable production. Each township manages poorer quality hill ground as common grazing for cattle and sheep.

crop Cultivated plant or the yield of cultivated plant for a given season or harvest.

cross-compliance A mechanism that links direct payments to compliance by farmers with basic standards concerning the environment, food safety, animal and plant health, and animal welfare, as well as the requirement of maintaining land in good agricultural and environmental condition. Cross-compliance is an important tool for integrating environmental requirements into the Common Agricultural Policy.

cultivar Cultivated variety (from cultivated + variety, abbreviated as cv). A category of plants that are, firstly, below the level of a subspecies taxonomically and, secondly, found only in cultivation. It is an international term denoting certain cultivated plants that are clearly distinguishable from others by stated characteristics and that retain their distinguishing characters when reproduced under specific conditions.

ecosystem A dynamic complex of plant, animal and microorganism communities and their non-living environment interacting as a functional unit.

ecosystem function An intrinsic ecosystem characteristic related to the set of conditions and processes whereby an ecosystem maintains its integrity (such as primary productivity, food chain, biogeochemical cycles). Ecosystem functions include such processes as decomposition, production, nutrient cycling, and fluxes of nutrients and energy.

ecosystem services The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth. The concept 'ecosystem goods and services' is synonymous with ecosystem services.

eutrophication Eutrophication, or more precisely hypertrophication, is the ecosystem response to the addition of artificial or natural substances, such as nitrates and phosphates, through fertilizers or sewage, to an aquatic system.

genetic diversity The variety of genes within a particular population, species, variety or breed.

genetic resources Genetic material of plants, animals or microorganisms, including modern cultivars and breeds, primitive varieties and breeds, landraces and wild/weedy relatives of crop plants or domesticated animals, of value as a resource for future generations of humanity.

green infrastructure The subregional network of protected sites, nature reserves, green spaces, and greenway linkages. The linkages include river corridors and flood plains, migration routes and features of the landscape, which are of importance as wildlife corridors. Green infrastructure should provide for multifunctional uses, i.e. wildlife, recreational and cultural experience, as well as delivering ecological services, such as flood protection and microclimate control. It should also operate at all spatial scales from urban centres through to open countryside.

habitat The physical location or type of environment in which an organism or biological population lives or occurs.

hyperparasitism A condition in which a secondary parasite develops within a previously existing parasite.

induced systemic resistance (ISR) Refers to a state of enhanced defensive capacity developed by a plant when appropriately stimulated. ISR is not the creation of resistance where there is none, but the activation of latent innate immune responses that are expressed upon subsequent, so-called 'challenge' inoculation with a pathogen. ISR occurs naturally as a result of colonization of the roots by beneficial soil-borne microorganisms, such as plant-growth-promoting rhizobacteria and mycorrhizal fungi.

integrated pest management (IPM) An approach to the management and control of agricultural pests which relies on site and condition-specific information to manage pest populations below a level that causes economic injury and that minimizes risks to humans and the natural environment. Although any among a wide range of pest control agents may be used (including chemical sprays), IPM generally stresses the use of alternatives, such as crop rotations, mechanical cultivation and biological agents, where such methods are deemed to be effective.

land use The spatial aspects of all human activities on the land and the way in which the land surface is adapted, or could be adapted, to serve human needs. Land use refers to how a specific piece of land is allocated: its purpose, need or use (e.g. agriculture, industry, residential or nature).

landscape The traits, patterns and structure of a specific geographic area, including its biological composition, its physical environment and its anthropogenic or social patterns. An area where interacting ecosystems are grouped and repeated in similar form.

landscape management Measures aiming at preserving landscape or controlling its transformations caused by anthropic activities or natural events.

microbe A microorganism, especially a pathogenic bacterium.

microorganism An organism that can be seen only with the aid of a microscope and that typically consists of only a single cell. Microorganisms include bacteria, protozoans and certain algae and fungi.

mouldboard ploughing To grow crops regularly in less fertile areas, the soil must be turned to bring nutrients to the surface. A major advance was the mouldboard plough, which not only cuts furrows with a share (cutting blade) but also turns the soil.

multifunctional agriculture Multifunctionality or multifunctional agriculture are terms used to indicate generally that agriculture can produce various non-commodity outputs in addition to food.

native species Plants, animals, fungi and microorganisms that occur naturally in a given area or region.

parasitoid An organism that spends a significant portion of its life history attached to or within a single host organism in a relationship that is in essence parasitic; unlike a true parasite, however, it ultimately sterilizes or kills, and sometimes consumes, the host.

pathogen A microorganism that can cause disease in other organisms. It may be present in sewage, run-off from animal farms, swimming pools, contaminated shellfish, etc.

precision agriculture Precision farming or satellite farming is a farming management concept based on observing and responding to intra-field variations. Today, precision agriculture is about whole farm management with the goal of optimizing returns on inputs while preserving resources. It relies on new technologies like satellite imagery, information technology, and geospatial tools. It is also aided by farmers' ability to locate their precise position in a field using satellite positioning system like the GPS or other global navigation satellite system.

protected area A geographically defined area that is designated or regulated and managed to achieve specific conservation objectives.

resilience The ability of an ecosystem to return to its original state after being disturbed.

salinization The increase in salt concentration in an environmental medium, notably soil. It is also known as salination.

semi-natural habitat Although there is no common definition, semi-natural habitats are generally considered to be any habitat where human-induced changes can be detected or that is human managed but which still seems a natural habitat in terms of species diversity and species interrelation complexity.

soil sealing Changing the nature of the soil such that it behaves as an impermeable medium (for example, compaction by agricultural machinery). Soil sealing is also used to describe the covering or sealing of the soil surface by impervious materials, for example, concrete, metal, glass, tarmac and plastic.

species A group of organisms capable of interbreeding freely with each other but not with members of other species.

stakeholder People or organizations which are vital to the success or failure of an organization or project in reaching its goals. The primary stakeholders are (a) those needed for permission, approval and financial support, and (b) those who are directly affected by the activities of the organization or project. Secondary stakeholders are those who are indirectly affected. Tertiary stakeholders are those who are not affected or involved, but who can influence opinions either for or against.

sustainable agriculture Type of farming that can make use of nature's goods and services while producing a sufficient yield in an economically, environmentally and socially rewarding way, preserving resources for future generations.

sustainable use The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.

threatened species A species that is facing an extremely high risk of extinction in the wild in the immediate (critically endangered), near (endangered) or medium-term (vulnerable) future.

variety Plant grouping, within a single botanical taxon of the lowest known rank, defined by the reproducible expression of its distinguishing and other genetic characteristics.

virulence In an ecological context, virulence can be defined as the host's parasite-induced loss of fitness. Virulence can be understood in terms of proximate causes (those specific traits of the pathogen that help make the host ill) and ultimate causes (the evolutionary pressures that lead to virulent traits occurring in a pathogen strain).

water infiltration The downward entry of water into soil. Also called percolation. A high rate of infiltration means that soil moisture for crops will be higher. Many conservation practices, such as conservation tillage, reduce rates of run-off and increase infiltration rates.

wetlands Transitional areas between terrestrial and aquatic ecosystems in which the water table is usually at or near the surface or the land is covered by shallow water. Wetlands can include tidal mudflats, natural ponds, marshes, potholes, wet meadows, bogs, peatlands, freshwater swamps, mangroves, lakes, rivers and even some coral reefs.

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