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Scientific evidence showing the impacts of nature restoration actions on food productivity

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Contents

Abstract

This report is a narrative review of the effects reported in the scientific literature (peer-reviewed and indexed scientific publications showing quantitative evidence) about the relationships between a selection of nature restoration practices and food production. The reported effects are extracted from systematic reviews, meta-analyses and individual papers. As a narrative review, this is not a representative sample of all the available studies conducted on the topic.

This report starts with an overview of the EU's legislative and policy frameworks that contribute to nature restoration. Then, it shows some evidence of the impacts of multiple farming practices that can contribute to nature restoration, providing key definitions and interrelationships. It presents further evidence of the impact of restoration measures on two key natural aspects for food productivity: soil quality and insect pollination. It continues with a review of the effects in food production of restoration measures applied in forest, in marine and in freshwater ecosystems. The last sections present the scarce information of cascade effects on other food security aspects than food productivity, and a recap of the missing aspects related to climate change mitigation and adaptation. Finally, this report concludes with a reflection of the limitations and major gaps found during the analysis.

Although we cannot extract a quantitative estimate without a proper meta-analysis, our review suggests that nature restoration measures have a remarkably positive impact on food productivity in the long-term, while most of the short-term impacts are context- and species-dependant. Thus, we consider that the restoration of degraded and overexploited ecosystems is an insurance policy to ensure the long-term sustainability and resilience of our food systems.

Executive summary

This report is a narrative review of the effects reported in the scientific literature (peer-reviewed and indexed scientific publications showing quantitative evidence) about the relationships between a selection of nature restoration practices and food production. The reported effects are extracted from systematic reviews, meta-analyses and individual papers. As a narrative review, this is not a representative sample of all the available studies conducted on the topic. Given that the selected publications analyse the environmental impacts of nature restoration practices, and most of these analyses are framed as environmental or ecological studies, most of the reported effects are positive.

Nature **restoration measures in farmland** generally consist of a variety of sustainable agricultural practices that have the potential to regenerate or increase the functionality of agroecosystems, while avoiding the depletion of natural resources such as soil, water and biodiversity. From the selected publications, we consider two aspects being as relevant for food productivity: the most direct effects on yield, and the effects on other elements and ecological processes that sustain the long-term productive capability and resilience of agroecosystems, like soil fertility, water retention capacity or avoidance of soil erosion.

No-tillage leads to a significant restoration of soil quality, even more if this is combined with organic fertilisation. When no-tillage is combined with cover crops, it can maintain or even increase crop yield and reduce costs while enhancing soil fertility. The effects vary depending on the crop and the climatic conditions, but overall no-tillage improves the soil characteristics (organic matter, infiltration, biological activity, etc.) compared with conventional tillage.

Mineral fertilisers are considered to play an important role in ensuring food productivity. Still, a wide range of studies indicate that there is considerable scope for reducing or stopping the use of mineral fertilisers without reducing yields. Precision farming, nitrification inhibitors, biofertilisers and integrated nutrient management are examples of viable alternatives that can reduce costs and avoid the pollution and greenhouse gas effects of nutrients surpluses. Identifying the most cost-effective technique requires an analysis of each crop and its context.

Pesticides protect plants or plant products from pests and diseases. However, some studies show that (aside from other consequences on the environment and health) their cost and side-effects on pollinators can actually decrease the economic returns of crops. A large-scale study indicates that pesticide use could be reduced by more than 40% without negative effects on productivity or profitability in most of the farms. Based on several meta-analyses, crop diversification alone is demonstrated to enhance pest and disease control by 63%, while integrated pest management can maintain or even improve some crops compared to herbicide use. Another alternative, biological control and/or the introduction of natural pest enemies can in some cases, not only control pests, but also increase the average crop yield. All these practices can reduce the dependence of farms on chemical pesticides. However, it is important to highlight that these are potential effects. The interactions between pest dynamics, plant growth and yields are complex and context-dependent, hence observed effects are highly variable.

Organic farming (production systems which avoid or largely exclude the use of synthetically compounded inputs) typically leads to lower yields than conventional farming. The yield gap between organic and conventional farming strongly depends on the crop (broadly from 5 to 39%), although it tends to decrease with time and decreases more sharply if it is combined with diversification practices. Also, organic products have several documented and potential benefits for human health.

Crop diversification is confirmed as a beneficial practice for biodiversity, pollination, natural pest control, nutrient cycling, soil fertility and water regulation without compromising crop production or even enhancing it (by *ca.* 14%). The magnitude of the positive effects depends on the type of soil and the choice of crop. The economic advantages of reducing insecticide applications and increasing yields through crop diversification have been estimated at 7.5% for some countries. Intercropping has been widely observed to deliver higher and more stable grain yields and even to improve its nutritional quality. Cover crops prevent soil erosion and improve infiltration, and there is a lot of evidence showing that legume cover crops can also increase yields.

Numerous synthesis research papers indicate that agroforestry practices (the inclusion of woody perennials with crops or livestock) have a positive effect on soil quality and erosion, carbon sequestration, biodiversity, pollination, pest- and disease control and water retention, while they show few or no trade-offs on productivity compared with conventional agriculture. The inclusion of landscape features in farms (not necessarily as agroforestry systems), which increases landscape complexity, has similar positive effects. There is evidence of their pest-control effects (in particular around arable land) and pollination (emphasised

by floral abundance). An example is the 1.4-fold increase in pest control and the 1.7-fold increase in pollination observed in landscapes with high edge density. Only in some cases do these positive effects translate into higher yields.

A common denominator of most of the publications reviewed is that the combination of various sustainable agricultural practices multiply their positive effects on the environment and on food productivity. Actually, agroecology, the most integrative approach to farming, food and socio-economic systems, seem to produce the best results. Several meta-analyses and reviews conclude that agroecological practices have positive outcomes on food security through higher yields, improved nutritional content and stronger resilience and stability against climate and socio-economic disturbances. A global scenario analysis points to the need to tackle not only farming practices but also food waste and meat consumption to find a viable food production system.

Natural insects' pollination is known to support yields, food quality and economic returns to farmers. A study estimates that a collapse in pollinators could cause a drop of 1-2% in the global GDP. Scientific evidence shows a great potential of **nature restoration measures to support pollinators** by providing habitats with high quality food, nesting, and overwintering resources or by reducing their exposure to pesticides. In some cases, especially where pollen is a limiting factor, food productivity can be enhanced by pollinators' abundance and diversity. Some articles have reported increases in crop yield following the introduction of wildflower strips and field margins in farmlands (e.g. +42% in avocado, +12% in blueberry yields). Maintaining high floral diversity and perennial floral plants is essential for the effectiveness of these measures. At a larger scale, agricultural diversification has also proven to enhance biodiversity, pollination, and pest control without compromising crop yields. The type of habitat surrounding crop fields has a strong effect on crop pollination and agricultural production; the magnitude of this effect is distance-dependent.

Soil is a crucial mediator between nature restoration measures and food production. For instance, severely eroded croplands in the EU contribute to a loss in agricultural productivity estimated at €1.25 billion per year, while a similar impact worldwide is modelled to cost $8 billion annually. Among the possible practices, conversion from arable land to grassland showed the highest soil organic carbon sequestration rates, followed by ley cropping systems and cover crops. Leaving land fallow and increased earthworm presence have notable benefits for soil health, with the latter found to increase crop yield by up to 25%. Practices such as cover crops, catch crops and green manuring may increase water infiltration and retention capacity by one-third with respect to conventional farming methods, and by nearly two-thirds when including perennial grasses, agroforestry or managed forest. The allocation of 12-28% of European arable land to combinations of alternative management practices can resulted in a soil organic carbon sequestration of 549-2141 Mt CO_2 equivalent by 2100. Soil conservation practices (e.g. reduced tillage, cover crops, plant residues, stone walls, grass margins and contour farming) have reduced soil loss by water erosion *ca*. 9.5% in EU lands during the period 2000-2016. However, a strong package of soil conservation practices is needed to further reduce soil erosion in areas with losses greater than the sustainable rates.

The **restoration measures applied in forest ecosystems**, such as increasing the coverage of natural forest, have positive effects both on pollinator abundance and on river fish biomass. The distribution of the forest, the landscape heterogeneity and the creation of landscape corridors positively influence the abundance and richness of pollinators. Planted native trees can provide similar support for insect pollinators as original forest habitats. Other practices such as forest thinning or planting adequate species in fire-prone areas have been associated with increased production of forage, potential increased production of honey and increased pollinator abundance.

A starting point towards the **restoration of marine ecosystems** is the protection of certain areas. A global study indicates that having 30% of the ocean covered by multi-purpose protected areas is compatible with maintaining access to fishing grounds that provide 89% of the global catch. Avoiding the degradation of key habitats, like coral reefs or mangroves, results in higher productivity (35% higher in a study of corals). Around 80% of properly enforced marine protected areas have been observed to have a positive spillover effect on surrounding fisheries, and this effect can increase gradually over decades. The spillover effect is of major importance around no-take zones, with an example of catches raised 5-fold in a period of only four years and beneficial side effects in fishers' income, tourism, social wellbeing and the regeneration of distant fisheries. The active re-creation of some benthic habitats, like oyster reefs or mangroves, has remarkably increased the production of fish, crustaceans and other invertebrates that may become the prey of commercial species. The restoration of seagrass meadows, technically improved in recent years, enhance juvenile fish populations positively affect their recruitment and total biomass. A meta-analysis demonstrates the cost-effectiveness of seagrass restoration actions based only on their effects on commercial species. Seagrass restoration measures, even if covering relatively small areas, have continuous positive effects on biomass and many other ecosystem services but require long-term commitments. On the negative side, the restoration of sites with polluted sediments may remobilise toxic elements that can end up in the food chain. This review highlights that, in contrast with farming practices, sustainable fishing and aquaculture practices (e.g. halting overfishing, establishing fisheries restricted areas, increasing the biosecurity of aquaculture, restorative aquaculture) are not usually considered in the literature as restoration measures, even if they might effectively restore biodiversity and fish biomass.

Despite the active field of research on river restoration and biodiversity (natural processes), there is little evidence of the **impact of freshwater habitats' restoration on food productivity**. Some observations point to the relevance of wetland restoration to reduce nitrogen and phosphorus inputs from land into water systems, while at the same time other important ecosystem services can be improved. Floodplains' restoration can support growth rates of juvenile fish and primary productivity to feed them. Inland fisheries can be enhanced by river-wetland filling, the improvement of riparian buffer habitats and riverine ecosystem connectivity. Seed banks and the monitoring of sedge meadows can be important tools for analysing the success of restored (farmed) wetlands.

The literature review shows that specific restoration measures are often context-dependent and, thus, their design should be purpose-specific and take into consideration the complex ecological and socio-economic settings. The appropriateness of specific restoration measures should be considered at local level. Unfortunately, there is little scientific evidence of the effectiveness of restoration efforts over time. This is a problem for large-scale scientific estimations that are made to support management decisions. We consider that science cannot yet provide an estimation of the consequences of multiple nature restoration measures in multiple sectors at larger (e.g. continental) scales, particularly if one considers the complex interactions generated by the different land- or marine-planning options available for different management interests.

Although we cannot extract a quantitative estimate without a proper meta-analysis, our review suggests that nature restoration measures have a remarkably positive impact on food productivity in the long-term, while most of the short-term impacts are context- and species-dependant. Thus, **we consider that the restoration of degraded and overexploited ecosystems is an insurance policy to ensure the long-term sustainability and resilience of our food systems**.

1 Introduction

JRC Directorate D on Sustainable Resources has been required to compile in a few weeks scientific evidence highlighting the impacts of nature restoration on food security aspects.

The Society for Ecological Restoration defines **ecological restoration** as an "intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (SER, 2004). Traditionally, active restoration implies management techniques such as translocation, planting, or seedlings, while passive restoration entails no action apart from ceasing environmental pressures such as grazing or fishing. However, recent views advocate for a replacing this terminology by a continuum-based intervention framework, which is focused on the recovery of ecosystems regardless of the level of intervention needed (Chazdon *et al.*, 2021). There are also open debates about the kind of guidance and flexibility that should be offered to restoration practitioners and policy makers in view of the rapid scaling up of restoration investment (e.g. Higgs *et al.*, 2018). Ecological restoration includes a large variety of actions devoted to erosion control, reforestation, removal of non-native species, revegetation of disturbed areas, daylighting rivers or streams, reintroduction of native species, as well as improving the habitat and extending the distribution range of targeted species.

Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 1996). Food security is one of the main objectives of Sustainable Development Goals 2 (zero hunger), 14 (life below water) and 15 (life on land). The concept of food security has four main pillars: food availability, access to enough food, food quality and stability over time. These four pillars are intrinsically linked to each other and are underpinned by healthy ecosystems. However, the scientific evidence that measures the effectiveness of nature restoration actions tends to focus on the first pillar, food availability or productivity. This is the reason why **this report focuses on the links between nature restoration and food production**. The other pillars of food security would need further research to reveal their relationships with nature restoration.

This report collects and summarises quantitative evidence reflecting some of the effects of nature restoration measures on food productivity. This is a narrative review (i.e. not a systematic review) of selected peer-reviewed, impact factor publications. We screened several hundreds of publications, scrutinised more than 250, and extracted quantitative evidence from 185 of them (Table 1). This evidence-gathering exercise focuses only on direct, quantitative relationships between restoration measures and food productivity, not covering indirect effects from food productivity to food security, or effects of restoration measures on ecological or climate change aspects (see the 'concluding remarks' section). Given that the selection of publications was based on nature restoration practices, many aspects of the food systems and in particular the comparison with conventional food production, are missing in this work.

Table 1. Number and type of the selected publications.

	Type of publication			
Ecosystem type	Individual paper	Meta-analysis	Review	Total
Agro- and forest ecosystems (semi-natural)	14	8	2	24
Agro-ecosystems	67	43	7	117
Natural forests	6	0	0	6
Freshwater ecosystems	10	0	1	11
Marine ecosystems	19	3	5	27
Total	116	54	15	185

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2 EU policy context

2.1 Environmental policies

The backbone of EU's nature legislation are the Birds and the Habitats Directive (Directive 2009/147/EC and Council Directive 92/43/EEC respectively). The **Birds Directive** aims at maintaining the populations of around 500 wild bird species naturally occurring in the European Union. It allows for a sustainable exploitation of certain species, and it prescribes special conservation measures for a list of threaten species and for migratory species. It establishes a network of Special Protection Areas that are included in the Natura 2000 ecological network, set up under the Habitats Directive. Regarding restoration, the Birds Directive asks for re-establishing a sufficient diversity and area of habitats for all the species of birds (e.g. re-establishment of destroyed biotopes).

The objective of the **Habitats Directive** is the conservation of natural habitats and of wild fauna and flora in the European territory. It aims at establishing of measures to maintain or restore, at favourable conservation status, over 1000 animal and plant species and 200 habitat types listed in the directive's annexes as rare, threatened, or endemic. The Habitats Directive established the EU-wide Natura 2000 network of protected areas based on Sites of Community Importance that then turn into Special Areas of Conservation.

The Fitness check of the Birds and Habitats directives published in 2016 concluded that both directives supported all targets of the (previous) EU's Biodiversity Strategy, especially the restoration of ecosystem services under target 2. However, these directives alone could not deliver the EU's biodiversity targets without complementary action at EU and national level in other key policy sectors, such as agriculture and fisheries. The most recent initiatives launched under the EU Biodiversity Strategy for 2030 boost and reinforce the objectives of the Birds and Habitats Directives setting ambitious quantitative targets for the protection of habitats and species as well as for their restoration to good conservation status.

The **Water Framework Directive** (Directive 2000/60/EC) aims to protect and enhance aquatic ecosystems (both surface waters and groundwater) and promote sustainable water use across Europe. The primary objective is achieving good status of Europe's waters through integrated management plans and appropriate measures, including restoration actions. The fitness check of the EU water legislation published in 2021 acknowledged that the Water Framework Directive sets a proper governance framework for integrated water management, slowing down the deterioration of water status and reducing chemical pollution. Still, it recognises that good status depends also on restoration measures to address pressures from the past, which should have been better developed. Restoration measures (either to restore connectivity or to address pollution) can take long time before showing effects but the benefits outweigh the costs. The Commission has developed a guidance document[1] to assist Member States in identifying and prioritising barriers that could be removed to help achieve the Biodiversity Strategy's goal of restoring 25,000 km of rivers to be free-flowing. The main types of action are the removal of barriers and the restoration of floodplains and wetlands.

The EU **Marine Strategy Framework Directive** (Directive 2008/56/EC) was put in place to protect the marine ecosystems and biodiversity across Europe while ensuring a sustainable use of their resources. For this, EU Member States shall take the necessary measures to achieve or maintain good environmental status in the marine environment. The Marine Water Framework Directive starts to play an active horizontal role in restoring a good environmental status at the scale of the European Seas. The eleven descriptors of the directive raise awareness and start to quantify progress towards good environmental status on such diverse anthropogenic impacts than eutrophication, contaminants and plastics, biodiversity and physical disturbance. The first objective of this framework directive is to prevent the deterioration of the marine environment or, where practicable, restore marine ecosystems. Any action taken by Member States to restore marine ecosystem will contribute to achieve a better environmental status and, as such should be included in the programmes of measures under the marine directive. However, the highly aggregated assessment and reporting structure of the directive may prevent a proper follow up of restoration activities.

The EU **Invasive Alien Species Regulation** (Regulation (EU) 1143/2014) sets out rules to prevent, minimise and mitigate the adverse impact on biodiversity due to the introduction, and spread within the Union, of both intentional and unintentional invasive alien species. Member States obligations include *inter alia* the application of proportionate restoration measures to strengthen the ecosystems' resilience towards invasions, to repair the damage caused and to enhance the conservation status of species and their habitats.

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[1] https://ec.europa.eu/environment/publications/guidance-barrier-removal-river-restoration_en

More recently, the European Green Deal requested to restore nature across Europe as a basis to achieve the Union's biodiversity and climate change objectives. The ambition of the **EU Biodiversity Strategy for 2030** (COM/2020/380 final) is to ensure that that Europe's biodiversity is on the path to recovery by 2030 and that by 2050 all ecosystems are restored, resilient and adequately protected. The strategy underlines that protection alone is not enough to reverse biodiversity loss and commits to develop a proposal for legally-binding EU nature restoration targets to restore degraded ecosystems, in particular those with the potential to remove and store carbon and to prevent and reduce the impact of natural disasters. The Commission concluded an impact assessment and drafted a proposal for a new **nature restoration regulation** that is expected to be adopted in the coming weeks.

The ambitious vision of the new **EU Soil Strategy 2030** (COM/2021/699 final) is to have all EU soil ecosystems in a healthy condition by 2050. The Strategy proposes specific actions in relation to climate change mitigation, circular economy, biodiversity, desertification, soil restoration, soil monitoring, and citizen engagement to enable the transition to healthy soils. The Strategy considers proposing legally binding objectives in the context of the Nature Restoration Law to limit the drainage of wetlands and restore drained peatlands, as well as measures to enhance biodiversity in agricultural land that would contribute to conserving and increasing soil organic carbon. The European Commission will propose a **Soil Health Law** in 2023. Such a legal framework will contribute to the achievement of the Soil Strategy 2030 objectives, grant soils the same level of protection as water and air and improve the condition of soils to better provide the ecosystem services that we depend on.

The **New EU Forest Strategy for 2030** (COM/2021/572 final) is one of the flagship initiatives of the European Green Deal and builds on the EU Biodiversity Strategy for 2030. The Forest Strategy recognises the multifunctional role of forests and sets up a process to develop a more ambitious framework for sustainable forest management. Protecting and restoring EU's forest ecosystems and biodiversity as well as adopting biodiversity-friendly forest management practices, are necessary to combat climate change, reverse biodiversity loss and ensure resilient and multifunctional forest ecosystems. Forest habitats and landscapes in good condition can enhance the condition of agro-ecosystems in an integrated ecosystem-based approach. Restoration of forest ecosystems can deliver benefits also at landscape level in an integrated mosaic of synergistic ecosystems including forests, agro-ecosystems, grasslands, soils, and water. The new CAP (for 2023-2027) offers increased flexibility to design forest-related interventions according to national needs and specificities; the recommendations to Member States encourage, among other, protecting and restoring forest ecosystems to reach good condition of habitats and species. The Commission will strive to increase the uptake of rural development funds available for the purposes of the EU Forest Strategy.

2.2 Agricultural policies

Since the introduction of agri-environmental measures in 1992 to steer European agriculture towards more environmentally sustainable practices, the EU's **Common Agricultural Policy (CAP)** has become an essential instrument for maintaining the environmental integrity of European agroecosystems. One of the CAP general objectives for the programming period 2023-2027 is to support and strengthen environmental protection in European rural areas. This environmental vocation is detailed in three specific objectives (art. 6 of the CAP Strategic Plans regulation):

- to contribute to climate change mitigation and adaptation;
- to foster sustainable development and efficient management of natural resources;
- to contribute to halting and reversing biodiversity loss, enhance ecosystem services and preserve habitats and landscapes.

The renewed CAP should reflect a higher level of environmental and climate ambition. For this, Member States are provided with different tools organised in the so-called green architecture: enhanced conditionality, sectoral interventions and eco-schemes in the first pillar, and agri-environmental-climate measures in the second pillar. While conditionality includes mandatory good agricultural practices and legal requirements, eco-schemes (voluntary for farmers but mandatory to set up for Member States) and agri-environmental-climate measures are voluntary commitments for which farmers receive additional payments.

The Commission sets the objectives, the types of interventions and the way they are financed, while the Member States themselves build the green architecture. This is done based on an identification of regional environmental needs, within the framework of the specific objectives mentioned above.

Particularly relevant is the shift from compliance with certain sustainable agricultural practices to actually achieving an improved environmental and climate performance of agriculture. This new delivery model has been adopted in the new CAP cycle and the **CAP Strategic Plan Regulation** (Regulation (EU) 2021/2115) sets a common framework for the monitoring and evaluation of the results.

This framework of identifying specific needs at Member State level and the requirement to achieve concrete results within ambitious environmental objectives makes the CAP strategic plans a potentially effective tool to implement restoration actions in European agroecosystems. These objectives, especially those related to biodiversity and ecosystem services, cannot be achieved without a solid intervention logic, which includes measures to restore the function of these ecosystems.

2.3 Fisheries policies

The last reform of the EU's **Common Fisheries Policy** from 2013 (Regulation (EU) No 1380/2013) was meant to set sustainable catch limits with the objective to restore stocks, maintain healthy ecosystems and safeguard stable, profitable fisheries for the EU fleet. Its first objective is to ensure that the activities of the fishing and aquaculture sectors are environmentally sustainable in the long-term and are managed properly to achieve economic, social and employment benefits. It also fixes the objective of progressively restoring and maintaining populations of fish stocks above biomass levels capable of producing maximum sustainable yield. To fulfil these objectives the European Union shall adopt **conservation measures**, such as measures to minimise the impact of fishing on the marine environment or measures necessary for compliance with obligations under Union environmental legislation (notably the Marine Strategy Framework Directive and the Habitats Directive). Therefore, these measures could contain nature restoration actions.

The reformed common fisheries policy came along with the set-up of a new **European Maritime and Fisheries Fund** (Regulation (EU) No 508/2014) to facilitate its implementation. Among the priorities for this fund there is the protection and restoration of aquatic biodiversity and ecosystems as well as the enhancement of ecosystems related to aquaculture. In particular, the fund can finance under shared management any measure related to the protection and restoration of marine biodiversity and ecosystems, and compensation regimes in the framework of sustainable fishing activities. A new **European Maritime, Fisheries and Aquaculture Fund** was adopted in 2021 (Regulation (EU) 2021/1139) keeping as a priority "fostering sustainable fisheries and the restoration and conservation of aquatic biological resources" and as one of the specific objectives "contributing to the protection and restoration of aquatic biodiversity and ecosystems".

The **EU Biodiversity Strategy for 2030** reiterates the need to restore marine ecosystems to 'good environmental status'. Some of the foreseen actions are the full implementation of the Common Fisheries Policy and Marine Strategy Framework Directive, the restoration of carbon-rich ecosystems, the restoration of important fish spawning and nursery areas, a new action plan to conserve fisheries resources and protect marine ecosystems, and measures to limit the use of fishing gear most harmful to biodiversity (specifically reducing seabed damage and by-catch).

3 Evidence of the impacts of farming practices having a potential to contribute to nature restoration

Nature restoration measures in farmland generally consist of a variety of sustainable agricultural practices that have the potential to achieve a balance between farming and nature: agricultural production should be achieved non depleting land, air, soil, water, plant and animal health and welfare, and supporting biodiversity. Pressures linked to farming combined with the challenges of food security and climate change, are causing mounting tensions in food systems. High impact factor scientific papers support that nature restoration efforts can help reverse declines in terrestrial biodiversity caused by habitat conversion and overexploitation. It is suggested that these efforts are economically feasible and consistent with broader sustainability goals, while at the same time able to maintain the provision of food for a growing human population (Leclère *et al.*, 2020).

The EU's Green Deal transformations for the agricultural sector are especially reflected in the Farm-to-Fork and Biodiversity strategies. Several studies (cited and reviewed in Barreiro-Hurle *et al.*, 2021) have recently tried to assess the impact of specific aspects of both strategies on agricultural production, focusing on the lower use of pesticides, the reduction of nutrient losses, an increase of land under organic farming, and an increased area under high diversity landscape features. Mainly based on economic modelling approaches, these studies, unsurprisingly, concluded that the reduction of inputs and land will lead to a considerable decrease in agricultural production. However, as described in Barreiro-Hurle *et al.*, 2021, the studies have several caveats, among others, they (i) do not consider the full scope of the two strategies and (ii) neglect positive feedback effects on agricultural production that can come along with more environmental-friendly production (e.g. increase in biodiversity and improved soil health) and enhanced sustainability of the food systems. Accordingly, additional work is needed to provide a full picture of the impact of the Farm-to-Fork and Biodiversity strategies (Barreiro-Hurle *et al.*, 2021).

Most of the effects of farming practices reviewed and compiled in this section fall under the category of short-term impacts (i.e. observed in less than 5 years). However, (i) the indirect side-effects affecting some soil properties (e.g. carbon content), (ii) the indirect side-effects on biodiversity, and (iii) the development of agroforestry practices act on longer timeframes (a decade or more).

Box 1. Conservation agriculture

Conservation agriculture is a farming approach that aims at preserving the long-term health of soil. The European Confederation for Conservation Agriculture defines it as a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil management techniques protect the soil from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources, water and air, while optimizing yields (ECAF, 2022).

The three key components of conservation agriculture are: (i) minimum soil disturbance (no or reduced tillage), (ii) maintenance of soil covers, and (iii) crop diversity and crop rotations. Some evidence on each of these three sets of practices is provided here. However, bundles of practices can have more positive synergistic impacts on the environment (Baaken, 2022).

3.1 No-tillage and reduced tillage

No-tillage, or zero tillage, refers to a practice in which a crop is sown directly into soil not disturbed through tillage since the harvest of the previous crop. Reduced tillage (including minimum tillage, subsoil tillage, non-inversion or shallow inversion) refers to methods applying lower degrees of soil disturbance compared to conventional tillage, which involves soil inversion (Derpsch *et al.*, 2014). So far, there is no robust scientific conclusion about the impact of different tillage practices.

The soil erosion by water is affected by tillage, depending on the depth, direction and timing of plowing, the type of tillage equipment used, and the number of passages made. Reduced tillage or no-till practices are effective in reducing soil erosion by water and leaching of nutrient into ground water. According to literature experimental results, the no till or reduced tillage may reduce soil loss by water erosion in the range of 65-75% (Nyakatawa *et al.*, 2001)[2].

A four-year field study in Spain of corn fields under no-tillage combined with organic (cow slurry) or inorganic (mineral) fertilisation showed a significant restoration of soil quality in both cases (lower soil acidity and enhanced organic matter content). Soil quality index increased from 13.8% to 67.6% for organic plots and from 13.4% to 44.4% for inorganic plots over a period of 4 years (Mijangos *et al.*, 2012).

A six-year field study in Italy showed that no-tillage with cover crops in arable agro-ecosystems led to soil fertility restoration while maintaining or enhancing crop yield and reducing costs. No-tillage with cover crops maintained wheat, maize and soybean yields, increased soil organic matter from 20% to 30% compared to conventional tillage. Similarly, soil total nitrogen increased from 21% to 28% compared to conventional tillage. The study concluded that replacing conventional tillage with no-tillage and winter cover crops enhances long-term soil fertility in fine-textured soils under temperate climates (Boselli *et al.*, 2020). Another no-tillage with cover crops study in an arid irrigated cropping system in California, USA, showed that soil aggregation, water infiltration rates, carbon content, nitrogen, water extractable organic carbon and organic nitrogen, residue cover, and biological activity were all increased relative to conventional tillage with and without cover crops. However, effects varied by depth with no-tillage increasing soil bulk density by 12% in the 0-15 cm depth and 10% in the 15-30 cm depth (Mitchell *et al.*, 2017).

However, an ongoing systematic review of 16 meta-analyses, all including data collected in Europe, shows that the impacts of no-tillage and reduced tillage on crop yield are inconsistent[3]. More specifically:

- For no-tillage: 7 results reported no effect (i.e. no variation of crop yield), 7 showed a negative effect (i.e. decrease of crop yield), 2 reported a positive effect (i.e. increase of crop yield), and 1 showed an uncertain effect.
- For reduced tillage: 3 out of 7 results reported a negative impact, 2 showed no effect, and 2 reported uncertain effect.

3.2 Diversification, intercropping and cover crops

Crop diversification was found to enhance crop production (+14%), associated biodiversity (+24%), and several supporting and regulating ecosystem services including water quality (+51%), pest and disease control (+63%) and soil quality (+11%) (Beillouin, 2021). A review of 98 meta-analyses concluded that a combination of agricultural diversification measures including crop and non-crop diversification was found to enhance biodiversity, pollination, pest control, nutrient cycling, soil fertility, and water regulation without compromising crop yields (Tamburini *et al.*, 2020). Diversification practices had a significant positive impact on organic yields (see under organic farming). Diversification with legumes or non-legumes improved soil fertility differently, the former being most beneficial for volcanic soils (with +18% plant biomass production in bioassays and +26% soil inorganic nitrogen compared to the low diversity management) and the latter for ferralsols (with +39% plant biomass production in bioassays, and +46% soil phosphorous, +26% soil carbon, +5% pH) (Sauvadet *et al.*, 2021). There is multi-country evidence that crop diversification significantly reduced populations of two key pests, reduced (on average) insecticide applications by 70%, increased grain yields by 5% and delivered an economic advantage of 7.5% (Gurr *et al.*, 2016). Widespread adoption of diversification practices shows promise to contribute to biodiversity conservation and food security from local to global scales.

Intercropping is a farming practice that involves cultivating two or more crop species (i.e. crop mixture cropping) or genotypes (i.e. cultivar mixture cropping) in the same area and coexisting for a time so that they interact agronomically. A literature review reinforced with field experiments and observations found intercropping to lead to higher and more stable grain yield (0.33 versus 0.27 kg/m^2) and higher cereal protein concentration (11.1 versus 9.8%) than the mean sole crop. Intercropping is particularly suited for low-nitrogen availability systems, but further understanding is required to propose generic crop management procedures (Bedoussac *et al.*, 2015). Shrub intercropping in the Sahel led to 126% higher millet grain yields when averaged across all fertiliser treatments (Bright *et al.*, 2021).

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[2] See also the Universal Soil Loss Equation (USLE) factsheet at http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm

[3] These results are part of a comprehensive database of agricultural practices that will be available soon in https://wikis.ec.europa.eu/display/IMAP/Home

Cover crops are grown to provide vegetative cover between rows of main crops in orchards and vineyards, or in the period between two main arable crops to prevent erosion and minimize the risk of surface runoff by improving the infiltration. They are temporary crops that can be cut and removed or incorporated into the soil. Based on various experimental site studies, it is estimated that cover crops may reduce soil loss by water erosion in the range of 15%-25% (Nyakatawa *et al.*, 2001; Verstraeten *et al.*, 2002; Panagos *et al.*, 2015a). Cover cropping with legumes is significantly beneficial for yield while non-legume cover crops can decrease yield. Data meta-analyses of arable farmland in California and in the Mediterranean region showed that food crop yield was 16% higher with legume cover crops and 7% lower with non-legumes, compared to plots without cover crops (Shackelford *et al.*, 2019). Replacing a fallow with legume cover crops led to a mean yield increase of 25% (Quemada *et al.*, 2013). Meta-analyses from Nordic countries show 6% average yield increase with legume and mixed cover crops and 3% decrease with non-legume cover crops (Valkama *et al.*, 2015). A meta-analysis of fruit yield and quality showed 9% yield and 7% fruit weight increase with legume cover crops (Fang *et al.*, 2021). Non-legume cover crops resulted in 11% yield decrease and no effect on fruit weight. A comparison of cover crops with grain or vegetable crops showed no effect of cover crops on the former and higher yields for the latter (Osipitan *et al.*, 2018). Several studies of no-tillage and cover crops show significant positive impacts on soil health (see the no-tillage and soil quality sections).

3.3 Reduction of fertilisers

Mineral fertilisers are considered to play an important role in ensuring food security. However, especially nitrogen surplus contributes to serious atmospheric pollution (Cohen *et al.*, 2017), degradation of vegetation and biodiversity (Cape *et al.*, 2009), climate change through nitrous oxide emissions (Frank *et al.*, 2019), ground and surface water degradation (Relabais *et al.*, 2009; Smith and Schindler, 2009; van Grinsven, 2010), and impacts on freshwater and marine ecosystems (Seitzinger *et al.*, 2010). Accordingly, the management of nitrogen is a crucial component of reaching sustainable food systems. One option to manage nitrogen more efficiently is precision farming, which has a high potential to decrease negative environmental effects of agricultural production while at the same time increasing the income of farmers and the quality of agricultural production (Finger *et al.*, 2019). Nitrification inhibitors are another technology that can be an economic viable solution to increase both crop yields and nitrogen use efficiency (Fellman *et al.*, 2021). A recent modelling study found that mobilizing a range of nitrogen mitigation options could increase global food security while respecting nitrogen surplus boundaries, leading to a reduction of 590 million people at risk of hunger by 2050 compared to 2010 (Chang *et al.*, 2021).

A wide range of studies indicate that there is considerable scope for reducing or stopping mineral fertiliser uses without reducing yields. No significant effect of mineral fertiliser (inorganic nitrogen) was detected in a cumulative field study of 294 oilseed rape fields that yield was limited by pollinators rather than nutrient availability (Catarino *et al.*, 2019a). Empirical analysis based on field surveys coupled with experimental trials, where nitrogen input was manipulated under real farming conditions, showed no significant effect of high-nitrogen application on winter wheat yields in conventional farms (Catarino *et al.*, 2019b).

Biofertilisers and integrated nutrient management can often fill the mineral fertilisers' gap. Biofertilisers are living microbes that enhance plant nutrition by either mobilising or increasing nutrient availability in soils, presenting a promising strategy to reduce dependency on inorganic fertilisers (Mitter *et al.*, 2021). For example, *Rhodopseudomonas palustris* strains TN114 and PP803 were found to be effective biofertilisers (Kantachote *et al.*, 2016): TN114 was the most effective for increasing grain yield in organic paddy fields while PP803 was the most effective in saline paddy fields. Substitution with biofertilisers also strongly reduces methane emissions.

Integrated management of phosphorus, organic sources, and beneficial microbes was found to significantly improve the dry matter partitioning of maize in semiarid regions. Dry matter partitioning is the process by which plants distribute their biomass from the source organs (leaves and stems) to the storage organs (grains), potentially affecting yields. Compost application at sowing time along with poultry manure (5 tons per hectare), 2 weeks before sowing, increased dry matter partitioning significantly, as did the incorporation of legume residues (Amanullah *et al.*, 2019).

Manure from healthy animals is a crucial fodder source for soil organisms and therefore stimulating a healthy, fertile soil. However, the quality of manure matters. Manure containing pollutants such as antibiotics, pathogens and heavy metals threatens the ecosystem's intactness.

3.4 Reduction of pesticides

A pesticide is aimed at preventing, destroying, or controlling a harmful organism ('pest') or disease, or it protects plants or plant products during production, storage and transport. The term includes herbicides, fungicides, insecticides, acaricides, nematicides, molluscicides, rodenticides, growth regulators, repellents, rodenticides and biocides. As potentially responsible for side-effects in agro-systems, the goal of pesticide reduction strategies is to reduce the use of pesticides in cropping systems, while maintaining their productivity and economic profitability compared to systems based on intensive use of pesticides.

Integrated pest management is one of the main pesticide reduction strategies. It is defined as set of practices that carefully consider all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment[4]. Integrated pest management thus emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.

Meta-analyses of integrated pest management with and without herbicide showed improved crop yield for the former and no difference for the latter compared to herbicide use alone in the case of *Convolvulus arvensis* (weed) control (Davis *et al*, 2018), and improved crop yield without herbicide in the case of Canada thistle (*Cirsium arvense*) (Davis *et al.*, 2018). One meta-analysis on the effects of integrated pest management on perennial crops yields (vineyards and orchards), analysing individual studies from 162 different publications, found no significant difference in yields compared with conventional farms (Katayama *et al.*, 2019). Another meta-analysis (Himmelstein *et al.*, 2017) found an increase in yields under integrated pest management compared with no integrated pest management. Results in this case should be interpreted with caution in the context of the EU as they are based on studies conducted in Africa.

Hossard *et al.* (2016) studied the long term effect of low-input systems on wheat and maize yields and found that substantially reduced amount of pesticides (and mineral fertilisers) had no impact on maize yields while the impact of wheat yields was on average a reduction of 11-13%.

A cumulative field study of 294 oilseed rape fields between 2013 and 2016 showed that yield and gross margins are greater (15-40%) in fields with higher pollinator abundance than in fields with reduced pollinator abundance (Catarino, *et al.* 2019a). This effect is, however, strongly reduced by pesticide use. Greater yields may be achieved by either increasing agrochemicals or increasing bee abundance, but crop economic returns were only increased by the latter: pesticides did not increase yields while their costs reduced gross margins. Another study estimated that total pesticide use could be reduced by 42% (corresponding to an average reduction of 37, 47 and 60% of herbicide, fungicide and insecticide use, respectively) without any negative effects on either productivity or profitability in 59% of farms (Lechenet *et al.*, 2017). Also, the results of 95 meta-analyses integrating more than 5000 experiments on 120 crop species in 85 countries showed that crop diversification enhanced pest and disease control by 63% (Beillouin *et al.*, 2021).

Biological control methods involving the introduction of flower strips enhanced pest control by 16% (Albrecht *et al.*, 2020). A more specific study showed strong reductions in cereal leaf beetle larvae (-66%) and eggs (-44%) and resulting crop damage (-40%), and 10% increase in average crop yield in winter wheat (Tschumi *et al.*, 2016). The positive interactive effect between natural pest control and pollination increased oilseed rape yield by 23% with synergistic effects contributing 10% – and single contributions 6% and 7% respectively – thus reducing dependence on chemical pesticides (Sutter and Albrecht, 2016).

3.5 Organic farming

Organic farming systems are production systems that avoid or largely exclude the use of synthetically compounded inputs. In the EU, their certification is regulated according to the prescriptions of EU Regulation 2018/848. Organic farming is based on principles and practices promoting environmental protection and climate action, in particular to maintain soil fertility, animal and plant welfare, and to support biodiversity. It is in line with a growing demand for products produced using natural substances and processes. It does not consist of a single practice, but of combined application of several farming practices, such as:

- banning the use of genetically modified organisms;

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[4] https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en

- limiting the use of mineral fertilisers, herbicides and pesticides;
- prohibiting the use of hormones and restricting the use of antibiotics to only when necessary for animal health;
- crop rotation;
- growing nitrogen fixing plants and other green manure crops to restore the fertility of the soil;
- enhancing natural pest control.

Overall, organic yields are typically lower than conventional yields (Seufert *et al.*, 2012). On average, the yield gap ranges from 5% (for rain-fed legumes and perennials on weak-acidic to weak-alkaline soils), 13% (when best organic practices are used), to 34% lower yields (Lesur-Dumoulin *et al.*, 2017; Alvarez *et al.*, 2021).

The yield gap also depends strongly on the crop, estimated in one study at 37% for maize and wheat, and 19% for soybean (Dal Ferro *et al.*, 2019). For cereals in general it was estimated at 30%, at 25% for potatoes and at 16% in orchard/vineyard landscapes (Maggio *et al.*, 2008; Katayama *et al.*, 2019). A US study based on data collected from over 10,000 organic farmers and a total of 800,000 hectares of organic farmland showed a 20% average yield gap across all crops – however, several crops showed no significant difference in yield between organic and conventional production, and organic yields surpassed conventional yields for some hay crops (Kniss *et al.*, 2016). The yield gap for Durum wheat was on average 15%, resulting partly from the effects of air temperature, rainfall and weed infestation (Campiglia *et al.*, 2015).

Organic farms produced strawberries of significantly better quality than their conventional counterparts (Reganold *et al.*, 2010). Pollination was also more effective in strawberries (Andersson *et al.*, 2012) and field beans grown organically (Andersson *et al.*, 2014). Landscape heterogeneity further improved pollination and field bean yield in organic farms but not in conventional ones. However, organic farming in isolated landscapes did not improve pollination (Brittain *et al.*, 2010).

A study also shows a declining yield gap between organic and conventional farming with time progressed since conversion, coinciding with enhanced N-input efficiency of organic compared to other farming systems (Schrama *et al.*, 2018). Diversification practices further reduce this yield gap: a meta-dataset (115 studies containing more than 1000 observations) showed that multi-cropping and crop rotation substantially reduce the yield gap (from 19%±4% to 9±4% and 8±5%, respectively) (Ponisio *et al.*, 2015). Research studies typically do not account for co-production of fodder/forage through crop diversification techniques (rotations, multicropping, cover crops), which were found to be significantly more frequent in organic farming systems (Alvarez *et al.*, 2021). Organic systems with grass-clover increased soil fertility but reduced rotational crop yield (Shah *et al.*, 2017). Here the yield gap between organic and conventional systems varied between sites: the greatest yield gap was found for systems without manure application (31-65%), while for systems with manure and catch crops it was 28-35%.

3.6 Agroforestry

Agroforestry is a particular type of land-use system and technology where woody perennials (trees, shrubs, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals. It is a form of multiple cropping that can be considered at a range of spatial scales from field to landscape, and that satisfies at least three basic conditions: (i) there are at least two species that interact biologically; (ii) at least one of the species is a woody perennial; (iii) at least one of the plant species is managed for forage, annual or perennial crop production. This section is closely related to the ones on landscape features and on restoration measures applied in forests, since all of them explain some natural functions of woody vegetation. However, not all landscape features and restoration measures applied in forests can be considered agroforestry practices.

Agroforestry systems, compared to conventional agriculture, have a positive effect on a wide range of environmental/climate impacts and little or no trade-offs. In particular, agroforestry significantly increases soil nutrients' stocks, carbon sequestration, biodiversity, pollination, pest- and disease-control and water retention, while decreasing soil erosion and greenhouse gas emissions (Pumariño *et al.*, 2015; Torralba *et al.*, 2016; De Stefano and Jacobson, 2017; Shi *et al.*, 2018; Basche *et al.*, 2019; Kuyah *et al.*, 2019; Muchane *et al.*, 2020). Agroforestry systems can also yield similar or sometimes higher amounts of food products per hectare, while delivering more diversified types of products from the same land (Bayala *et al.*, 2012; Rivest *et al.*, 2013; Jezeer *et al.*, 2017; Félix *et al.*, 2018; Akinnifesi *et al.*, 2021). For example, agroforestry increased soil organic carbon stocks by 18% (Shi, *et al.* 2018), and was estimated to mitigate around 27.2 tons CO_2-equivalents per hectare per year, at least for the first 14 years after establishment (Kim *et al.*, 2016). Depending on the type of agroforestry system, biodiversity can increase by 40-50% considering only European data (Torralba, 2016).

3.7 Landscape features

Agricultural landscape features are small fragments of non-productive natural or semi-natural vegetation in agricultural landscapes that provide ecosystem services that affect soil health, pollination, pest control and crop yield in adjacent fields. Historically, farmers have taken advantage of the natural elements already present in the agricultural landscapes or have created them for various purposes: to use their wood, to create shelter for crops and livestock as well as windbreak barriers, to delimit parcels, or to be able to cultivate on land with steep slope. Examples considered here consist mainly of hedgerows, trees (in line or group or isolated), field margins, flower strips, and other planted areas. The presence of landscape features is also referred to as landscape complexity, and their removal as landscape simplification.

A recent second order synthesis (building on systematic reviews and meta-analyses) has documented an overall positive impact of landscape features / landscape complexity on biodiversity and ecosystem services (Baaken, 2022). The effect of landscape features on crop yield is more ambiguous: most of the studies did not inspect this question, and the ones that did found mixed impacts. A global synthesis (674 fields in 42 studies) showed that cascading effects of landscape simplification led to lower crop production (Dainese, *et al.* 2019).

In a meta-analysis of services provided by semi-natural landscape features, out of the publications reporting pest control effects, 81% reported positive effects (although 67% of these used as a proxy for pest control the abundance, diversity and predation or parasitism rates of natural enemies, which do not necessarily translate into reduced pest abundance or plant damage). Most positive effects were reported for arable crops. Of these publications, 52% recommended field boundary habitats such as hedgerows, hedgebase or field margins. Out of the publications reporting effects on pollination, 79% reported positive effects, of which 25% recommended field boundary habitats while 25% emphasized floral abundance irrespective of habitat type. Most publications reporting effects on soil erosion and soil organic matter reported positive effects (Holland, *et al.*, 2017).

In landscapes with high edge density pollination and pest control were found to increase 1.7 and 1.4-fold respectively (Martin *et al.*, 2019). A comparative study of landscape complexity effects on pollinators and natural enemies showed positive effects on bees and spiders but inconclusive effects on parasitoids and predatory beetles (Shackelford *et al.*, 2013).

Several studies (Carvalheiro *et al.*, 2011; Feltham *et al.*, 2015; Albrecht *et al.*, 2020; Muñoz *et al.*, 2021) point to significant impacts of flower strips, hedgerows and other landscape features on pollination rates or pollinators abundance, which in some cases are also translated into higher yields (see the section on pollination for details). One study estimated flower strips and hedgerows to enhance pest control by 16% (Albrecht *et al.*, 2020). In another study, flower proximity affected natural enemies and increased wheat yield by 15% (Mei *et al.*, 2021).

The maintenance of landscape features such as stone walls (and terraces) and buffer strips (grass margins) has positive effect in trapping sediments within the borders of the agricultural fields, therefore reducing soil erosion (Dabney *et al.*, 2009; Maetens *et al.*, 2012; Panagos *et al.*, 2015b). Dry stone walls are widespread landscape features in the Mediterranean region (e.g. Malta, Sicily, Cyprus, Balearic Islands, Aegean Islands) and can be effective in reducing runoff and soil erosion, especially in hilly areas. Grass margins are mainly located at the edge of the fields, between cropped areas (beetle banks) or bordering roads and tracks (roadside verge).

A synthesis for hedgerows and grass strips on arable land indicated that crop yield was reduced by 29% up to a distance twice the hedgerow height and increased by 6% beyond this up to a distance 20 times the hedgerow height. Parcels with hedgerows showed higher pest's predators diversity but not density, while those with grass strips showed higher predator density as well as diversity and lower aphid (small sap-sucking insects) density (van Vooren *et al.*, 2017).

In a study on landscape greening along with landscape features (sown wildflower strips and hedgerows) around 18 winter oil seed rape fields, insect pollination potential and pest predation increased on average by

10% and 13% respectively when the landscape-scale greening share (within a 1 km radius around focal fields) was increased from 6% to 26%. For pollination, the increase was 14% stronger in fields adjoining landscape features. However, neither significantly affected crop yield, of which agricultural management practices were the main determinants (Sutter *et al.*, 2018).

Box 2. Agroecology

Agroecology can be considered jointly as a science, a set of practices and a social movement. It integrates agricultural production, ecological principles, social impacts, economic performance, food sovereignty, right to food, social justice, governance issues, addressing the whole food system and beyond. The key agroecological principles that concern more specifically the ecological dimension of farming (and are, thus, more closely linked to restoration) are the following ones (HLPE, 2019):

- Soil heath. Secure and enhance soil health and functioning for improved plant growth, particularly by managing organic matter and by enhancing soil biological activity.
- Input reduction. Reduce or eliminate dependency on purchased inputs
- Recycling. Preferentially use local renewable resources and close as far as possible resource cycles of nutrients and biomass.
- Animal health. Ensure animal health and welfare.
- Biodiversity. Maintain and enhance diversity of species, functional diversity and genetic resources and maintain biodiversity in the agroecosystem.
- Synergy. Enhance positive ecological interaction, synergy, integration, and complementarity amongst the elements of agroecosystems.

Each of these principles can be linked to one or more of the farming practices described in this section.

Agroecology offers the possibility of win-win solutions: by building synergies across the positive effects of the individual farming practices, it can increase food production and food & nutrition security while restoring the ecosystem services and biodiversity that are essential for sustainable agricultural production (FAO, 2014).

4 Further evidence of the impacts of restoration measures on insect pollination

Given that 70% of the 124 global crops used directly for human consumption rely on or benefit from pollinators for their reproduction (Klein *et al.*, 2007), the loss of pollinators in agricultural land is a major threat to food production. Many studies have analyzed the importance of insect pollination for food production by conducting pollinator exclusion experiments. In most cases, open pollination (i.e. when pollinators are allowed to access the flowers) provided higher yields, fruit quality, fruit set and seed set, compared to cases where pollinators were excluded (Bartomeus *et al.*, 2014; Garratt *et al.*, 2014; Klein *et al.*, 2003; Geslin *et al.*, 2017; Wietzke *et al.*, 2018). Similarly, experiments where pollen was added manually have also shown higher yields (e.g., fruit and seed sets) compared to open pollination, indicating that for some crops in some areas there is pollen limitation (Holland *et al.*, 2020). Therefore, higher pollinator abundance could potentially translate into higher yields. Food production can be enhanced by pollinator abundance and/or pollinator diversity depending on the context (Woodcock et al., 2019), and many articles highlight the importance of wild bees and other non-bee wild pollinators for crop production (Blitzer *et al.*, 2016; Garibaldi *et al.*, 2013; Mallinger and Gratton, 2015; Bishop *et al.*, 2016; Grass *et al.*, 2018; Pérez-Méndez *et al.*, 2020). The loss of pollinators comes along with considerable economic costs, with a study estimating that the worldwide short-term welfare effects due to a collapse in pollinators could be between 1 and 2% of global GDP (Lippert *et al.*, 2021).

Despite their importance, insect pollinators are declining worldwide. The loss of their habitat, the use of pesticides, invasive species or the spread of pathogens are among their main threats (Potts *et al.*, 2010). Scientific evidence shows a great potential of nature restoration measures to support pollinators and pollination services by providing them habitat with food, nesting and overwintering resources or by reducing their exposure to pesticides. As insect pollinators are mobile organisms, restoration measures targeted to favour pollination services can cover multiple spatial scales, from local (e.g. wildflower strips) to field (e.g. organic farming) and landscape scale (e.g. restoration or preservation of semi-natural areas). Regarding temporal scales, the re-creation of adequate habitats for pollinators may take from short to medium time scales (i.e. from 1 to 10 years) but, once settled, their effect can be rapid.

At local scale, scientific evidence shows that the creation of wildflower strips and diverse field margins enhances pollinator richness and abundance, generally leading to an increase in pollination of adjacent crops (Feltham *et al.*, 2015; Martin *et al.*, 2019; Sutter *et al.*, 2018). Some articles have reported increases in crop yield through enhanced pollination service or reduction of pest damage following the implementation of wildflower strips and field margins in farmlands (e.g. 42% in avocado, 12.2% in blueberry, 10 to 15% in wheat) (Blaauw and Isaacs, 2014; Isaacs and Kirk, 2010; Mei *et al.*, 2021; Muñoz *et al.*, 2021).However, a recent review suggests that the effects of these local measures on yield through crop pollination are variable (Lowe *et al.*, 2021). To increase the effectiveness of these local restoration measures on the provision of pollination services, ensuring a high floral diversity and perennial floral plantings is essential (Albrecht *et al.*, 2020).

At field scale, agricultural management practices can affect pollination. Yet, their effects on pollination seem to be context dependent. While some authors show positive effects of organic farming on pollination (Andersson *et al.*, 2012; Andersson *et al.*, 2014), others found no significant differences between organic and conventional farming (Brittain *et al.*, 2010; Porcel *et al.*, 2018). As already stated in the section of 'diversification', a recent meta-analysis showed that agricultural diversification (including a variety of practices such as intercropping and crop rotation, non-crop diversification, organic farming, organic amendment and reduced tillage) enhanced biodiversity, pollination and pest control amongst other ecosystem services, without compromising crop yields (Tamburini *et al.*, 2020).

At landscape scale, the composition of the landscape matrix and the type of ecosystem surrounding crop fields have a strong positive effect on crop pollination and agricultural production (Carvalheiro *et al.*, 2010; Garibaldi *et al.*, 2011; Holland *et al.*, 2017; Morandin and Winston, 2006). Scientific evidence shows a positive relation between the presence of natural and semi-natural habitats and the provision of pest control and pollination services (e.g. significant increases in fruit set in almond and cherry, and in seed mass in sunflower crops) (Carvalheiro *et al.*, 2011; Holzschuh *et al.*, 2012; Klein *et al.*, 2012). The magnitude of these effects is distance dependent, with the highest benefits received near the natural/semi-natural patch. The effect of natural and semi-natural habitats directly on crop yield is explored by a small number of studies, which point out positive contributions for instance through the increase of bee abundance (Kremen *et al.*, 2004).

5 Further evidence of the impacts of restoration measures on soil quality

While the soil is itself an ecosystem, containing more than 25% of the planet's living organisms, it is also a crucial mediator of the impact of all terrestrial nature restoration measures on food production and security – including those described in the previous sections. Soil health, fertility and water retention capacity are indispensable for improving and maintaining crop yields and nutritional content, as well as food system resilience against climate change, drought and other pressures. Soil erosion is a serious problem affecting nearly all of Europe: approximately 12 million hectares of severely eroded croplands in the EU contribute to an annual loss in agricultural productivity estimated at 1.25 billion euro (Panagos *et al.*, 2016; Panagos *et al.*, 2018). Combining a biophysical and an economic model, a study estimates that the economic impact of soil erosion by water on the world economy may cause global annual costs of 8 billion US dollars, simultaneously impacting food security by reducing global agri-food production by 33.7 million tonnes with accompanying rises in agri-food world prices (Sartori *et al.*, 2019).

In addition to the impacts of specific farming practices on soil health and fertility already described in the previous sections, some general results are described below. The application of soil conservation practises (reduced tillage, cover crops, plant residues, terraces, contour farming and grass margins) had positive effect in reducing soil loss by water erosion by around 9.5% in the European Union lands in the period 2000-2016 (Panagos *et al.*, 2015c; Panagos *et al.*, 2020). In 2016, conservation tillage was applied in 22.4% of EU arable lands (+0.8% compared to 2010) and no-till farming has a share of 4.2%. (+0.2%). Cover crops have increased quite substantially in 6-years (2010–2016) as they were applied in 8.9% of EU arable lands, compared to 6.5% in 2010 (Borrelli and Panagos, 2020). The total number of grass margins in the EU have increased to 29% of the observed LUCAS points (+8% compared to 2012).

A study of the impact of six management practices in increasing soil organic carbon in soils concluded that conversion into grassland showed the highest soil organic carbon sequestration rates, ranging between 0.4 and 0.8 t of carbon per hectare per year, while the opposite extreme scenario (100% of grassland conversion into arable) gave cumulated losses of up to 2 Gt of carbon by 2100. Among the other practices, ley cropping systems (rotation of grass/legume crops with grain/tilled crops) and cover crops gave better performances than straw incorporation and reduced tillage. The allocation of 12 to 28% of European arable land to different alternative management practices combinations resulted in a potential soil organic carbon sequestration of 101–336 Mt CO_2 equivalent by 2020 and 549-2141 Mt CO_2 equivalent by 2100 (Lugato *et al.*, 2014). Leaving land fallow also contributes to soil health, resulting in a 18% increase in soil organic carbon (Kämpf *et al.*, 2016). Increased earthworm presence was found to stimulate plant growth – predominantly by releasing nitrogen locked away in residue and soil organic matter – thus increasing crop yield by 25% and aboveground biomass by 23%. Earthworms were found crucial for farming without nitrogen fertiliser (van Groenigen *et al.*, 2014).

A meta-analysis of conventional and sustainable farming methods showed that infiltration rates and water retention capacity increased under cover crops, catch crops and green manuring (mean = 34.8%, CI = 19.8-50.0%) and by including perennial grasses, agroforestry or managed forest (mean = 59.2%, CI = 18.2-100.2%) (Basche and DeLonge, 2019).

6 Evidence of the impacts of restoration measures in forest ecosystems

The literature review revealed an array of forest restoration measures affecting positively food production. The measures are in general associated with specific environmental traits, including biotic and abiotic characteristics of forest ecosystems. Therefore, forest and landscape features should be considered at local level for a proper understanding of the appropriateness of specific restoration measures. Regarding temporal scales, the restoration of forests habitats and species usually require long-term measures to show their effects.

Among the measures assessed, **increasing the proportion of natural forest** at landscape level has a clear positive effect on pollinator abundance (Taki *et al.*, 2011). Likewise, an increase in the proportion of forest area at catchment level was associated with an increase of river fish biomass (Tanentzap *et al.*, 2014).

The **share and distribution of natural forest** in the landscape mosaic are both key factors for pollinators. Several crop pollinator species depend on accessible (distance criterion) natural forests for their food and nest resources (i.e. nest in the cavities of natural trees). Similarly, replanting native trees, shrubs, and understory plants in degraded riparian habitats, has a positive effect on bee communities, which reach levels of richness and abundance equal to those found in nearby remnants of riparian habitat in good condition (Williams, 2011). The proportion of forest cover close to wildflower strips and **landscape heterogeneity** are influential landscape elements determining more complex ecosystem relations resulting in communities with increased abundance and richness of species, thus improving pollination services (Fabian *et al.*, 2013).

There is evidence indicating that conservation and restoration measures such as **forest thinning** (i.e. the selective removal of trees taken on to improve the growth rate or health of the remaining trees), and **plantation of resprouting species in fire-prone areas** provide enhanced ecosystem attributes associated with increased food production such as forage for livestock and potential production of honey (Moghli *et al.*, 2022). In addition, forest restoration through thinning could be oriented to create open canopy forest with increased plant diversity and plant production, thus benefiting pollinator abundance, specifically butterflies (Waltz and Covington, 2004).

Restoration measures increasing **landscapes corridors** positively affect pollination services. For instance, measures such as wooded and grassland corridors enhance connectivity in cropland-dominated landscapes. There is evidence indicating that wasp abundance in grass strips connected to forest edges improved notably, thus increasing pollination services (Holzschuh *et al.*, 2009).

Other benefits of forest restoration measures that could indirectly affect food production (like support to birds, mammals and herbivorous that can aid on weed control or seed dispersal; support of berries and mushrooms harvest; etc.) are identified as a gap in this section.

7 Evidence of the impacts of restoration measures in marine ecosystems

The restoration of marine ecosystems can follow a passive approach (the control or ban of harmful activities or threats for the ecosystems) or an active approach (with methods such as seeding and planting, introduction of species, removal of invasive species, creation of artificial substrates, or removal of contaminants). In the EU context, the MERCES project (http://www.merces-project.eu/) has done a wide compilation of marine restoration practices (see for instance Carballo-Cárdenas *et al.*, 2018; Morato *et al.*, 2018). In terms of time scales, some short-lived species (e.g. small pelagic fish) can be recovered rapidly after an improvement of their habitat or condition (including a decrease on their exploitation rate), while a proper restoration of benthic habitats and bioconstructors (e.g. seagrass meadows, some reefs) can take from 5 years to decades.

Regarding **passive restoration**, global models of the potential benefits of ocean protection have shown that protecting 30% of the ocean using a multi-objective solution could protect 89% of Representative Biodiversity Areas and 89% of threatened species, while at the same time maintain access to fishing grounds that provide 89% of global catch (data from 2,170 exploited species) (Jefferson *et al.*, 2022). At a more local scale, healthy coral reefs that did not suffer from erosion (i.e. losing of structural complexity) sustain fisheries productivity at least 35% higher than degraded ones (Rogers *et al.*, 2018). Protecting one hectare of mangroves has been associated with increased fish yields valued between $18,000 per year (de Groot *et al.*, 2012) and $37,500 per year (Aburto-Oropeza *et al.*, 2008).

The spillover effect (i.e. export of fish biomass) from marine protected areas towards adjacent fished areas was observed in 80% of the empirical studies analysed in a systematic review (Di Lorenzo *et al.*, 2016). This review highlighted that the protected areas must be properly enforced to allow fish recovery and, only then, fish spill across the boundaries because of higher population density inside the protected area.

A quantitative meta-analytical approach using 28 data sets from marine protected areas in Southern Europe concluded that protection had positive effects on the catch of the surrounding fisheries, with a mean increase from 2 to 4% per year over a period of at least 30 years (Vandeperre *et al.*, 2011). These effects depended on the size of the no-take area (i.e. area where fishing is not allowed) and on the duration of protection: the influence of the size is complex and sometimes contradictory, while a long timeframe is considered as necessary for the export functions.

After a complete fishing ban of four years within a no-take area in Torre Guaceto (Adriatic Sea), artisanal professional fishing in the buffer zone surrounding the no-take area had a catch per unit effort five-fold higher than unprotected areas farther away. With the resumption of fishing activities in the buffer zone, that value then declined and stabilized at a rate about 2.5 higher than the areas farther away from the no-take zone (Guidetti *et al.*, 2010). In the same protected area, high-quality Slow Food labels were assigned to several species of fish and agricultural products inside the terrestrial protected area, which also contributed to boost tourism and the local economy. Research and evidence gathering from the effects of fishery restrictions in Torre Guaceto on fish catch, fishermen income, labelled agricultural products, tourism and social conditions are compiled in Russi (2020). Moreover, the dispersal of plant fragments that are able to settle and grow and of seabream juveniles of two-banded seabream (*Diplodus vulgaris*) grown within the protected area can reach over 100 km away from the site, representing a high regeneration potential for other fisheries (Di Franco *et al.*, 2015).

The efficiency of closing areas to fishing should be evaluated on a case-by-case basis. Economically, it can be a more attractive solution when the value derived from spillover outweighs the value of fishing. The condition is more likely to be satisfied when the closed area is a net exporter of biomass and has higher costs of fishing, and for fish populations with settlement that depend on adult movement rather than larval passive dispersal (Sanchirico *et al.*, 2006).

The **re-creation or improvement of benthic habitats**, like oyster grow-out sites and artificial reefs, increases fish abundance and decrease the mortality and emigration of commercial fish species (Tallman and Forrester, 2007). An area of 10 m^2 of restored oyster reef is expected to yield an additional 2.6 kg per year of production of fish and large mobile crustaceans, meaning that a reef lasting 20 to 30 years would augment such a production by 38 to 50 kg per 10 m^2 (Peterson *et al.*, 2003). Oyster reefs enhance also the abundance of resident invertebrates that comprise more than 90% of juvenile fish prey biomass (Grabowski *et al.*, 2005). However, in the case study that generated these results, the increase in food availability did not affect the abundance of juvenile fish because food resources may not limit juvenile fish.

A meta-analysis of the outcomes of mangrove restoration reflects positive benefit-cost ratios ranging from 10.5 to 6.8 under variable discount rates, suggesting that mangrove restoration is a cost-effective form of ecosystem management (Su *et al.*, 2021). Overall, there was no difference between restored and natural mangroves in the production and diversity of fish, crab and other macrobenthic fauna.

Restoration of seagrass meadows has mostly been limited in extent due to previous experiences of low success, although the most recent experiments and protocols are promising. Incorporating positive species interactions into restoration methods appears to increase plant growth with little additional resource investment (Valdez *et al.*, 2020).The enhancement of juvenile fish by seagrass habitats was quantified through a meta-analysis of in southern Australia. Thirteen fish of commercial importance were identified as being recruitment enhanced in seagrass habitats, twelve of which were associated with sufficient life history data to allow for estimation of total biomass enhancement: the identified species were enhanced in seagrass by 0.98 kg/m^2 per year, equivalent to *ca.* $A230,000 per hectare per year. Having accounted for the time lag between fish recruiting to a seagrass site and entering the fishery and for a 3% annual discount rate, the meta-analysis finds that seagrass restoration efforts costing $A10,000 per hectare have a potential payback time of less than five years, and that restoration costing $A629,000 per hectare can be justified based on enhanced commercial fish recruitment where these twelve fish species are present (Blandon and zu Ermgassen, 2014).

Eelgrass restoration over only 6% of the total restored area in coastal lagoons of Virginia, USA, during a long-term commitment (20 years) was able to revive this essential habitat. The study estimates a total invertebrate biomass increased by *ca.* 700 t, finfish biomass by *ca.* 3000 t and a tendency to stabilization in nearly 20 years (Orth *et al.*, 2020). The restored area serves as a key steppingstone for the movement of fauna, including juveniles of many key fisheries species, along the east coast of the United States. Other quantified benefits include improved water clarity, enhanced carbon and nitrogen burial in sediments and erosion prevention. The well-developed meadows now foster productive and diverse animal communities and have prompted a parallel restoration for bay scallops.

On the negative side, the restoration of sites with polluted sediments remobilise trace and toxic elements that can end up filtered and accumulated in the edible tissues of commercial species such as mussels, risking human health (Parolini *et al.*, 2022). However, the results of this study suggest that the native mussels are safe for human consumption regardless of restoration activities.

The regulation and management of **fishing or aquaculture practices**, apart from no-take zones, is not commonly considered a restoration action at sea (in contrast with the farming practices on land presented in this report), although their effects are very effective to restore biodiversity and fish biomass. The comparison of the effective catch yields corrected with the local potential fish production of a highly and moderately overfished European shelf areas exploited by sea-bottom trawling, reveals that sustainable fisheries lead to substantially higher catches (by a factor of 2 to 3) than overfishing (Druon *et al.*, 2021).

One of the possible management measures are 'fisheries restricted areas' designed to maintain stocks and populations. A recently established fisheries restricted area in the central Adriatic Sea, the Jabuka/Pomo pit, has been recognised as a critical habitat for demersal species (in particular, hake and Norway lobster) (Russo *et al.*, 2018) and the monitoring activities carried out in the area show the positive effects of the closure, although the fishery restricted area is too recent to have peer-reviewed impact publications on the effects yet. The Jabuka/Pomo pit is quantitatively confirmed as sound and necessary since it is the most important spawning area (with good spawning performances) in the Adriatic for Norway lobster (Melaku Canu *et al.*, 2020). Experts consider that a combination of managed areas, control measures of effort and increase of selectivity is the most indicated approach for increasing sustainability and efficiency of fisheries (FAIRSEA, 2021).

The concept of restorative aquaculture merits some assessment in future studies. This is a type of commercial or subsistence aquaculture providing direct ecological benefits to the environment, with the potential to generate net-positive environmental outcomes (The Nature Conservancy, 2021). For example, seaweed aquaculture accounts for 51.3% of global mariculture production and can deliver a broad range of ecosystem services (source of food and industrial products, nature-based solution for climate change mitigation and adaptation, remediation of eutrophication, supporting biodiversity) (Duarte *et al.*, 2022).

8 Evidence of the impacts of restoration measures in freshwater ecosystems

Despite the importance of freshwater ecosystems for food provision (i.e. water supply for drinking, agriculture and industry; water purification; inland fisheries) and the existing practice restoring natural processes in freshwater ecosystems (e.g. Wohl *et al.* 2015), it is hard to find quantitative evidence of the effects of freshwater habitats' restoration on food productivity. This section collects some observations, but they rarely measure changes in food supply or yields.

Rising nitrate concentrations in freshwater are of concern throughout the developed world: for human health as well as due to eutrophication. **Wetland restoration** in agricultural areas can improve water quality by reducing concentrations of sediment, total phosphorus, and nitrate in runoff (Almendinger, 1998). There has been a 35% average decline in area of natural inland wetlands since 1970 (UNEP, 2021). Drainage of wetlands leads to deteriorated wetland conditions and lowered water tables (Bring *et al.*, 2020).

The costs of losing wetland ecosystem services are often overlooked in land-use planning (Gómez-Baggethun *et al.*, 2019). Multidisciplinary efforts are needed to integrate other benefits of wetland restoration, such as improvement of wildlife habitat and flood abatement, even if the restoration focus is on water-quality benefits. There are some proposed protocols to select wetland-restoration sites at the watershed scale, for example for improving wastewater from irrigated agricultural land (Comín *et al.*, 2014).

The Baltic Sea is one of the world's most oxygen-depleted seas. Scientists consider that the region requires large-scale restoration of wetland buffer zones to significantly reduce nitrogen and phosphorus inputs from land through rivers (Giergiczny *et al.*, 2021). A survey among citizens of the Baltic Sea region concluded that re-meandering, rewetting of floodplains, and restoration of wild marshes (i.e. natural wetland vegetation) or development of wetland agriculture, could gain a lot of public support in Europe (Giergiczny *et al.*, 2021).

Seed banks, an important source of regenerative material, can be a valuable resource for the restoration of farmed wetlands when the seeds survive periods of cultivation. A study in China reported consistently higher values of species richness and seed density in natural sedge meadows compared with those in soybean and paddy fields farmed. Most sedge meadow species disappeared when farmed for more than 10 years (Wang *et al.*, 2015). A study of rapid seedbank development in restored tidal freshwater wetlands suggested that seed banks are a useful metric of wetland restoration success because they integrate processes affecting growth and reproduction of standing vegetation. The density and richness of emerging seedlings from Kingman Marsh seed bank samples increased from less than 4 seedlings and 2 taxa in a 90-cm^2 sample in the year of restoration to more than 130 seedlings and 10 taxa in the same sample three years later (Middleton, 2003; Neff *et al.*, 2009).

In 2015, **inland fisheries** provided an amount of animal protein equivalent to the full dietary consumption of at least 158 million people. Higher reliance on wild-caught freshwater fish is associated with lower overall consumption of terrestrial animal-sourced food, but it is dependent upon the maintenance of healthy, freshwater habitats. About 90% of global catch from riverine fisheries comes from river basins with above-average stress levels (McIntyre *et al.*, 2016).

Long cumulative river-wetland filling (Beesley *et al.*, 2012) in temperate floodplain wetlands was shown to be associated with greater total abundances of newly recruited (0+) fish and better body condition; this was particularly true for common carp and carp gudgeon. Restoring floodplains support growth rates of juvenile fish and primary productivity (i.e. food for fish) along with other multiple benefits (Jeffres *et al.*, 2020; Serra-Llobet *et al.*, 2022).

A study demonstrating the importance of riparian buffer habitat and water temperature on the composition of food availability for fish species of concern (such as brook trout) emphasizes the need to include food web dynamics into riparian habitat restoration design to guide future rehabilitation projects (Albertson *et al.*, 2018).

Reduction of riverine ecosystem connectivity has long-lasting impacts on food webs. For example, the ecosystem role of anadromous fish has been affected by widespread riverine habitat fragmentation and other impacts mainly derived from anthropogenic sources, resulting in eradication and increased susceptibility to environmental factors. A study highlighting the benefits of increased connectivity between freshwater and ocean ecosystems demonstrates the significant role anadromous forage fish could play in improving specific fisheries and overall ecosystem functioning (Dias *et al.*, 2019). The large and recent amount of evidence analysing the restoration of river connectivity in Europe deserves further review.

9 Reflections on cascade effects on food security aspects

With this literature review we could not cover the influence that nature restoration may have on the sociological and equity aspects of food security, namely (i) access to enough food, (ii) food quality and (iii) stability over time. However, we present in this section some evidence gathered on the topic.

The scientific literature shows that many of the agricultural practices discussed in this report are key to achieving food security through higher yields, improved nutritional content and stronger resilience and stability against drought, climate change and other disturbances (e.g. war and conflicts). Effects on yields, resilience and other facets of food security are often mediated by improvements in aspects such as soil health and fertility, pollination efficiency, pest and disease control, and nutrient management.

A meta-analysis of the impact of agroecology on food security and nutrition noted positive outcomes of agroecological practices on food security and nutrition in 78% of the 56 studies reported. The positive outcomes are mostly linked to households in low- and middle-income countries. The most common agroecological practices with positive outcomes on food security and nutrition included crop diversification, agroforestry, mixed crop and livestock systems, and practices improving soil quality. There was also a slightly positive trend between the number of agroecological practices applied and the strength of the positive relationship, indicating that complexity in farm management can lead to additional benefits (Bezner Kerr *et al.*, 2021).

A review of the contribution of agroecology to selected human, financial and social indicators found evidence of agroecology's positive contribution to improving financial capital (financial capital increases using agroecological practices in 93 out of 147 comparisons (63%) compared to conventional agriculture) (D'annolfo *et al.*, 2017). However, data extracted does not provide statistically significant information on other human and social capital indicators.

A JRC report (i.e. grey literature without impact factor) found in 50% of the 172 papers reviewed a positive contribution of agroecological practices to food security, notably due to improved yields and/or a better economic situation of producers (Paracchini *et al*, 2020). For example, an improved use of organic fertilisers (with manure or compost) results in a significant improvement in yields. However, access to manure can often be a problem in the absence of significant crop-livestock integration. In fact, throughout different articles, the lack of access to inputs is a recurring issue, particularly for what concerns the improvement of soil fertility (manure, mineral fertilizer, leaf litter, etc.) remaining a major hindrance for food security. Diversified crop systems, including the introduction of agroforestry, improved household nutritional status and had positive links to better health conditions.

A scenario analysis compared agriculture as forecast by FAO (the baseline scenario) with scenarios of increased uptake of organic farming plus reduction in food waste and meat consumption (reduction in food-competing feed) (Muller *et al.*, 2017). The results showed that (1) switching to 100% organic farming with no other measure, production leads to increases in land use of 16-33% due to yield gaps on average 8% lower in organic yields. Land occupation increases further when the model includes the adverse effects of climate change. But (2) a partial conversion to organic production (40%) combined with 50% food wastage reduction and 100% reduction of food-competing feed components becomes viable, with equal or even reduced land demand compared to the reference scenario, even including the impacts of climate change.

10 Reflections on links between restoration, climate change and its consequences on land ecosystems

We do not specifically address the impact of nature restoration measures on climate change mitigation and adaptation, an important gap that needs to be filled by other studies. However, there are many synergies in terms of nature restoration measures that boost food security via increased long-term productivity and resilience while advancing climate change adaptation and mitigation. Many of these measures – including agroecological practices, conservation agriculture and agroforestry – have been partially covered in this document.

Climate change creates additional stresses on land, exacerbating existing risks to food systems. Increasing impacts on land are projected under all future greenhouse gas emission scenarios (IPCC, 2019). At the same time, an estimated 23% of total anthropogenic greenhouse gas emissions (2007-2016) derive from Agriculture, Forestry and Other Land Use (AFOLU). The total technical mitigation potential from crop and livestock activities and agroforestry is substantial, estimated as 2.3-9.6 Gt CO_2 equivalent per year by 2050 (medium confidence).

The IPCC special report (Chapter 6) identified five main land challenges: climate change mitigation, adaptation, desertification, land degradation, and food security. Nine options were found to deliver medium-to-large benefits for all five land challenges. These were: increased food productivity, improved cropland management, improved grazing land management, improved livestock management, agroforestry, forest management, increased soil organic carbon content, fire management and reduced post-harvest losses.

A range of integrated agricultural systems has been found to lead to low-carbon and climate-resilient pathways for sustainable food security, thus advancing both mitigation and adaptation goals. These include agroecology and conservation agriculture, which have been covered in this document. Specific outcomes include increased yield, yield stability and resilience via improved soil health (soil carbon sequestration and increased soil organic matter), prevention and reversal of soil erosion and land degradation, pest and disease control, and reduction of the use of mineral fertilisers. Agroecology has been proposed as a key set of practices in building climate resilience and enhancing adaptation of crop production systems. There is also considerable scientific evidence for the benefits of conservation agriculture (including cover crops, crop rotation and no-tillage) for soil health and carbon sequestration.

Another aspect associated to climate change is the proliferation of extreme events. There is also evidence (not screened in this report) that some restoration measures can help mitigating their effects. One example is a study in Central American which after Hurricane Mitch showed that farmers using diversification practices such as cover crops, intercropping, and agroforestry suffered less damage than their conventional monoculture neighbours (Altieri *et al*., 2015). Sustainable plots had 20 to 40 % more topsoil, greater soil moisture and less erosion and experienced lower economic losses than their conventional neighbours (Holt-Giménez, 2002). After Hurricane Ike hit Cuba in 2008, researchers found that diversified farms had losses of 50% compared to the 90-100% losses in neighbouring monocultures. Likewise, agroecologically managed farms showed a faster recovery than monoculture farms (Rosset *et al*., 2011).

11 Concluding remarks

A synopsis of the scientific evidence compiled in this report is presented in the executive summary. These concluding remarks highlight some gaps and challenges encountered while developing this report.

It should be noted that this report focuses solely on the benefits of nature restoration to food production, and does not cover other notable benefits like biodiversity support, carbon sequestration, aesthetic values, remediation of pollution and eutrophication or tourism and recreation. Future studies should address these important benefits. However, our screening of the scientific literature highlighted **the scarcity of quantitative scientific evidence, especially long-term, of the effectiveness of restoration efforts**.

The socio-economic aspects linked to restoration and food productivity (including socio-economic consequences of restoration actions and cost-benefit analyses) are too loosely covered in the literature to draw any conclusion. This is particularly the case if one considers the complex interactions generated by different land- or marine-planning options available in response to different management interests. Only local data or complex modelling exercises can provide some estimates. However, the modelling approaches (as well as the scientific publications) tend to focus on either ecological or economic aspects and generally fail to capture the wide range of cause-effect mechanisms. **We consider that science cannot yet provide an estimation of the consequences of multiple nature restoration measures in multiple sectors at continental scales.** A compilation of best practices or quantitative evidence, like those presented in this report, can instead be a good starting point.

Although without a proper meta-analysis we cannot extract a quantitative estimate, our review suggests that **nature restoration measures have a remarkably positive impact on the environment and on food productivity in the long term (also in terms of yield stabilisation), while most of the short-term impacts are context- and species-dependant.** Thus, we consider that the restoration of degraded and overexploited ecosystems is an insurance policy to ensure the long-term sustainability and resilience of our food systems.

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