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Regenerative agriculture in Europe

A critical analysis of contributions to European Union Farm to Fork and Biodiversity Strategies

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Foreword

Agricultural production systems are currently severely threatening climate stability and ecosystem resilience and constitute a large driver of environmental degradation. For example, there are severe impacts through the loss of species biodiversity and ecosystem services such as pollination, increase in soil erosion, declines in soil fertility, downstream damage to water resources and degradation of coastal ecosystems. An increased sustainability and resilience of agricultural production in the face of these crises must be based on a systemic view that not only analyses how to mitigate the effects of the current multitude of global crises on agriculture, but also indicates what specific transformations are needed to reduce the contribution of agricultural production itself to these crises.

The latest analyses by the United Nations Intergovernmental Panel on Climate Change (UN IPCC) and the recent Climate Change Conference of the Parties (COP26) in Glasgow in November 2021, confirm the need for urgent actions (before 2030) to reduce greenhouse gas (GHG) emissions so that the world can meet its Paris Agreement commitments to limit global warming to less than 1.5 or 2 °C above pre-industrial levels. Agricultural production is an important source of GHG. Several of the 17 UN Sustainable Development Goals (SDGs) are particularly relevant to sustainable agriculture, including SDG 2 'Zero hunger', SDG 3 'Good health and well-being', SDG 12 'Responsible production and consumption', SDG 13 'Climate action' and SDG 15 'Life on land'. The European Union (EU) Commission intends to make Europe the first climate-neutral continent by 2050 through implementing the European Green Deal. One important part of the European Green Deal is the Farm to Fork Strategy which outlines multiple transformative changes of EU agriculture until 2030. The Farm to Fork Strategy has the goal of European food production becoming the global standard for sustainability and aims to enhance opportunities for all operators in the food value chain and support the introduction of new technologies and scientific discoveries, and to combine these with increasing public awareness and demand for sustainable food. Also of importance is the EU Biodiversity Strategy which is closely linked to the Farm to Fork Strategy and was published simultaneously. The two strategies have several overlapping goals and targets; for example, taken together they aim to bring a diverse and resilient nature back to agricultural landscapes (as well as to forests, seas, coasts and urban areas). There is a strong consensus among EU member states about the importance of reaching these goals, but the challenge is to find mechanisms for reaching them along many different and locally adapted pathways.

With the goals and commitments defined by the two strategies in mind, a group of experts, nominated by their national science academies (EASAC member academies), worked during 2021 and made a critical review of the available options for sustainable agriculture in Europe. This report summarises the group's analyses, conclusions and advice for policy-makers.

The Farm to Fork and Biodiversity Strategies include a range of ambitious targets intended to put the EU food system on a transformative path towards greater sustainability. Those with the greatest relevance to agricultural production include the following:

- agriculture to contribute to a reduction of at least 55% in net GHG emissions by 2030;
- reduction by 50% of the use and risk of chemical pesticides, and reduction in use of more hazardous pesticides by 50% by 2030;
- reduction of nutrient losses by at least 50% while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilisers by at least 20% by 2030;
- reduction by 50% of sales of antimicrobials for farmed animals and in aquaculture by 2030;
- reaching 25% of agricultural land under organic farming by 2030;
- a minimum of 10% area under high-diversity landscape features.

The ambitious agenda is intended to be achieved by substantially strengthening diverse efforts to tackle climate change, protect the environment, and restore and preserve biodiversity in European agricultural landscapes. Here, the concept of regenerative agriculture is increasingly viewed as a promising set of tools to meet the main goals and targets of both the Farm to Fork and Biodiversity Strategies.

This report provides a critical analysis of the main components of regenerative agriculture: soil-health restoration, carbon capture and storage, and reversal of biodiversity loss. On the basis of an extensive review of existing meta-analyses and systematic reviews on farming practices commonly viewed as part of regenerative agriculture (i.e. intended to increase carbon capture and storage and enhance biodiversity), the EASAC Working Group has analysed the potential synergies and trade-offs that may occur at different scales from plot- and farm- to landscape scale, and derived evidence-based policy recommendations for meeting Green Deal targets.

The EASAC analyses demonstrate that many of the agricultural practices studied show synergies between carbon capture and storage and enhancing biodiversity (although sometimes with modest effect sizes), while not having clear large negative effects on food production, especially in the long term. There are also examples of clear trade-offs (e.g. food production after conversion of arable land to grasslands). Practices that show synergies include increased diversification within and among crops, introduction of permanent and perennial crops, and keeping green plant cover on all farm fields during all seasons. Such practices should be given considerable attention in plans by member states for implementation of the new Common Agricultural Policy. The report also emphasises that the capacity of grasslands to capture and store carbon may have been underestimated, and that permanent grasslands should thus be considered when developing policies on carbon farming in Europe.

It is EASAC's intention that this report and the analyses it contains should not only highlight the options for a sustainable agriculture in the EU, but should also help EU policy-makers and other stakeholders to prioritise their future policies, legislation and investments for this important sector.

Christina Moberg
EASAC President

Abbreviations

CAP	Common Agricultural Policy
CORDEX	Coordinated Regional Downscaling Experiment
EASAC	European Academies' Science Advisory Council
EEA	European Environment Agency
EU	European Union
GHG	Greenhouse gas
HLPE	High Level Panel of Experts
HNV	High Nature Value
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
UN	United Nations
UNFSS	United Nations Food Systems Summit

Summary

Globally, agriculture is the main driver of deforestation and land conversion, and food systems account for more than a third of global greenhouse gas (GHG) emissions, making food production a major contributor to climate change. At the same time, agriculture is extremely vulnerable to shifts and variability in temperature and rainfall, which are expected to increase because of climate change. More and more farmers, and particularly the smallholders who produce about a third of the world's food, are struggling with harvest and livestock losses while trying to adapt to increasingly irregular weather conditions. However, the United Nations Food System Summit (UNFSS) in September 2021 pointed out that the global food system also holds important keys to keeping global warming below 2 °C. With the right investments in research, innovation and smallholder farming, UNFSS argued that it is possible to transform global food systems in ways that simultaneously reduce climate risks, hunger and poverty, and improve access to healthy diets while also enhancing biodiversity.

As part of the European Green Deal, the Farm to Fork and Biodiversity Strategies together address the challenging transition of European Union (EU) agriculture towards a net 55% reduction in GHG emissions by 2030, with the aim of making European food production the global standard for sustainability. This is to be achieved by substantially strengthening diverse efforts to tackle climate change, protect the environment, and restore and preserve biodiversity in European agricultural landscapes. Here, the concept of regenerative agriculture is increasingly viewed as a promising set of principles to meet the main goals and targets of the Farm to Fork and Biodiversity Strategies.

Regenerative agriculture aims to maintain agricultural productivity, increase biodiversity, and in particular restore and maintain soil biodiversity, and enhance ecosystem services including carbon capture and storage. Our evaluation of the concept of regenerative agriculture has revealed some clear advantages when it comes to developing policies for sustainable agriculture. Regenerative agriculture is not viewed as defined *a priori* by a given set of rules and practices; instead the goals that should be achieved are set and then practices and new technologies are adopted over time which contribute to achieve these goals. Hence the concept is viewed as broader and less prescriptive compared with other related concepts such as agroecology, organic farming, conservation farming, and carbon farming, and does not exclude the use of, for example, modern plant and animal breeding technology, tilling, use of inorganic fertilisers or pesticides, but aims for a limited, more targeted use.

Although regenerative agriculture has no clear consensus definition and may have many components, there are two main characteristic features: *1. Restoration, particularly of soil health,* including increasing the capacity of soils to *capture and store carbon* to mitigate climate change. 2. *Reversal of biodiversity loss.* Despite the increasing interest and application of regenerative agriculture in farming and its wide adoption by agricultural businesses, a critical scientific analysis of its effectiveness has not been conducted.

This report provides a critical analysis of the main components of regenerative agriculture: soil restoration, carbon capture and storage, and reversal of biodiversity loss. On the basis of an extensive review of existing meta-analyses and systematic reviews on farming practices commonly viewed as part of regenerative agriculture (i.e. intended to increase carbon capture and storage and enhance biodiversity), the report analyses the potential synergies and trade-offs that may occur at different scales from plot- and farm- to landscape scale, and derives evidence-based policy recommendations for meeting Green Deal targets. Given the global nature of the problems regenerative agriculture is meant to address, the report analyses regenerative agriculture in the EU in its global food system context, where agriculture is viewed as a subsystem of the food system.

Our results demonstrate that many of the analysed practices show synergies between carbon capture and storage and enhancing biodiversity (although sometimes with modest effect sizes), while not having clear large negative effects on food production, especially in the long term. Practices that show synergies include the following: *increased diversification within and among crops, introduction of permanent and perennial crops, expanded agroforestry and intercropping, keeping green plant cover on all farm fields during all seasons, and reduced tillage.* We also found some examples of clear trade-offs (e.g. conversion of arable land to grasslands increase carbon storage and biodiversity but food production decrease). Practices that show clear synergistic effects should be given considerable attention in plans by member states for implementation of the new Common Agricultural Policy (CAP). Recent studies also suggest that the capacity of grasslands to capture and store carbon may have been underestimated, and that permanent grasslands be considered more strongly when developing policies on carbon farming in Europe.

Regenerative agriculture as it is currently presented (Oberč and Arroyo Schnell 2020) does not explicitly

address *larger scales* (landscape and regional) despite the fact that several processes, particularly for maintaining biodiversity, are operating at these larger scales. This is a clear weakness of the concept. Existing meta-analyses and systematic reviews analysing the evidence base for processes influencing biodiversity at the landscape/regional scales show that, through better coordination of management practices at the landscape/regional scales, it is possible to simultaneously enhance biodiversity and carbon capture and storage. Financial schemes should therefore not only benefit individual farmers but also communities and associations of farmers managing landscapes in a coordinated way. At the landscape scale, restoration efforts for enhancing biodiversity should be prioritised where there are existing semi-natural habitat patches, establishing connection between restored sites and the semi-natural habitat patches. Our conclusion from this analysis is that there is clear evidence for the importance of addressing processes for enhancing biodiversity at the landscape and regional scales, and that only targeting the farm scale is insufficient.

The EU Biodiversity Strategy has the ambitious goal of reaching 25% of all croplands under organic farming cultivation by 2030. In this context it is important to critically evaluate whether organic farming or conventional farming with landscape diversification is more effective and cost-effective from the viewpoint of crop production and the maintenance of biodiversity. Our literature review suggests that allocating resources to the diversification and restoration of semi-natural habitats in conventionally farmed agricultural landscapes would be at least equally important for biodiversity as prioritising organic agriculture. This would especially be the case if the trend towards intensification within organic farming continues, because organic intensification diminishes the positive effects of organic management of arable land.

Although many of the reviewed practices can provide win–win solutions, we emphasise that the application of any particular practice(s) is highly *context-dependent*. The highest co-benefits can be achieved when the practices are coordinated at the landscape scale and fit the local environmental and socio-economic conditions.

On the basis of the evidence presented in the report we recommend that the policies implement the following strategies and measures.

A General policy recommendations

Successful implementation of the Farm to Fork and Biodiversity Strategies depends on the following:

- Policy development and implementation made in a global food system context.
- Addressing a shift from a dominant focus on the volume of food produced to the nutritional and environmental quality of food; this requires a holistic food system approach.
- Always considering potential impacts in the production chain of changes in the consumption chain, such as dietary shifts and reduction of food waste.
- Emphasising the multifunctional dimensions of agricultural landscapes, including ecosystem services, recreation, tourism, and human health, particularly close to urban centres.
- Providing predictable and long-term agri-environmental support to farmers to enable a sustainable shift to regenerative agriculture.
- Flexible long-term support for sustainable innovative and local transformative change initiatives, such as adopting new regenerative practices, new or modified crops and machinery, innovative business models, agri-business start-ups, institutional systems for coordination at landscape-scale, innovative urban–rural linkages, etc.
- Substantial increase in EU and national investments in localised education, training and extension services.
- Avoiding exporting negative environmental externalities to countries outside the EU.

B Policy recommendations at the farm scale

EASAC recommends placing special emphasis on support for the following practices, which show synergies between carbon capture and storage, particularly in soils, and enhancing biodiversity, while having no or limited negative effects on food production:

- Increased diversification within and among crops.
- Introduction of permanent and perennial crops.
- Expanded agroforestry and intercropping.
- Strive for green plant cover on all farm fields during all seasons, reduce tilling.
- Targeted support systems and information campaigns about CAP eco-schemes to farmers managing sites with higher natural values.
- CAP eco-schemes should also target smallholder farms since smaller field sizes in general support higher biodiversity and ecosystem service.

C Policy recommendations for the landscape scale

- Develop schemes that support better coordination of management practices that simultaneously enhance biodiversity and carbon capture and reduce net GHG emissions at the landscape/regional scales.

- Stimulate schemes that benefit not only individual farmers but also communities and groups of farmers, for example within the framework of National Rural Development Programmes.

- Promote sustainable innovations for rural–urban–rural cycles of nutrients.

- Adapt and develop meaningful indicators that can be easily measurable over large spatial scales, such as field size or the extent of high-diversity landscape features.

Policy recommendations for restoration in the agricultural landscape

- Prioritise restoration in agricultural landscapes where there is an existing green infrastructure containing semi-natural habitat patches.

- Besides creation of new high-diversity landscape features, prioritise conservation and management of existing ones.

- Support restoration measures that increase landscape complexity.

Policy recommendations for localisation

- Land should be used for products that can be cultivated in the long-term without sacrificing regulating and supporting ecosystem services, often with the aim of shortening the production-consumption chain.

- More flexibility should be given to farmers in their management decisions. This could be achieved by employing the concept of adaptive management: as long as the targets (food production, carbon storage, biodiversity, ecosystem services) are maintained, farmers should have flexibility in choosing and varying the management options from a toolkit that suits the local conditions.

Policy recommendations for animal husbandry

- A shift from intensive year-round stabling animal husbandry towards extensive pastoral systems should be supported by CAP eco-schemes. Grazing and mowing in High Nature Value grasslands should be recognised as best practice for maintaining biodiversity and ecosystem services and providing high-quality meat products.

D Policy recommendations for tree planting in the agricultural landscape

- Mixtures of tree species planted in agricultural landscapes should be carefully selected with regard to their traits and genetics to be able to survive under different climate scenarios and generate valuable ecosystem services.

- Such trees should become more common in many intensified agricultural landscapes in regions with a historical presence of trees in the landscape.

- Prioritise and support trees as high-diversity landscape features in arable landscapes and in agroforestry.

- Increase the number of trees in urban and peri-urban areas, since these may also contribute to improve local climate and livelihoods; public outreach and environmental education.

- Avoid tree planting in regions where open habitats constitute the native vegetation, such as in (semi-) arid regions.

1 Introduction

1.1 Focus and rationale for the study

Over the past three decades it has become increasingly evident that farming and food systems need fundamental transformations to enable pathways towards sustainability (UNFSS 2021; European Commission (2020); European Commission, DG Research and Innovation 2020). This report takes as a first point of departure the goals and commitments made in the recent European Commission's Green Deal, and specifically the **Biodiversity** and **Farm to Fork Strategies**, for dealing with both **climate change** and **biodiversity loss** while at the same time securing production of an **adequate supply of nutritious food**. These strategies taken together raise several important questions: To what extent are these goals compatible and possible to reach without substantial increases in costs for consumers or dietary changes, and without reduction in livelihoods for farmers? Will the current area under agricultural production be sufficient and to what extent are there important synergies where innovation in farming practices may enable pathways to simultaneously reach these goals? Are there important trade-offs that will be difficult or very costly to address? There is an urgency in addressing these questions: the United Nations Food System Summit in September 2021 pointed out that time is extremely limited and that, globally, we may have only about a decade to transform the entire food system (UNFSS 2021).

The second point of departure for this report is a critical analysis of the recent and promising, but from a scientific point of view largely untested, concept of **regenerative agriculture**. According to Oberč and Arroyo Schnell (2020), regenerative agriculture is defined as a system of farming principles that aims to maintain agricultural productivity, increase biodiversity and in particular restore and maintain soil biodiversity, and enhance ecosystem services including carbon capture and storage (see also Newton *et al.* 2020; Schreefel *et al.* 2020; Giller *et al.* 2021). In contrast to other related concepts, regenerative agriculture is not viewed as defined *a priori* by a given set of rules and practices, instead the goals that should be achieved are set and then practices and new technologies are adopted over time which contribute to achieve these goals. Here we critically analyse the scientific evidence base for how regenerative agriculture, as the concept is currently interpreted, can contribute to achieving the European Union (EU) goals for biodiversity, carbon storage and food production.

The report gives a global background to understanding the food system in chapter 2, including an overview of shifting global production and trade. In chapter 3, we analyse the climate and biodiversity challenges facing agriculture in Europe. However, the main messages from this report are based on the analyses in chapter 4, where we have conducted an extensive literature review based on existing meta-analyse and systematic reviews on farming practices intended to increase carbon capture and storage and enhance biodiversity and where data were available, also analysed impact on food production. We specifically analysed the potential synergies and trade-offs that may occur at different scales from plot- and farm- to landscape scale. In our analysis we also paid specific attention to the role and untapped potential of various restoration interventions in the agricultural landscape for increasing carbon storage and enhancing biodiversity. This is receiving increasing international attention and viewed by the scientific community as something that should be urgently addressed (e.g. Rockström 2021). We also want to emphasise that the report puts regenerative agriculture in the EU in its global food system context, where agriculture is viewed as a subsystem of the food system. It is important to stress that EU agriculture includes a wide range of farming systems over a wide range of agroecological conditions from South to North, East to West, and across elevation gradients. Therefore the range of sustainability challenges is equally broad. Chapter 4 provides an analysis of the strengths and weaknesses of regenerative agriculture, and addresses some economic and social dimensions. We end with chapter 5 highlighting evidence-based recommendations for policy.

As a final point we emphasise that this report focuses on ecological sustainability, ecological resilience, and restoration of natural resources and ecosystems in agricultural landscapes in the EU, with a particular focus on biodiversity, carbon capture and storage, and food production. Hence, economic and social dimensions of sustainability are covered less, but included to the extent needed for understanding the key interlinkages between these and the ecological regeneration and restoration needs, including necessary social and institutional innovations for achieving the stated goals.

1.2 The shifting policy arena in the EU: The EU Green Deal—Farm to Fork Strategy, Biodiversity Strategy, and the Common Agricultural Policy

The President of the European Commission, Ursula von der Leyen, presented the European Green Deal Strategy in December 2019 as 'Europe's new growth strategy', intending to make Europe the first climate-neutral continent by 2050. The EU Recovery Plan (27 May 2020) puts a strong emphasis on green recovery to stimulate joint (public/private) investment efforts towards sustainable technologies and activities, especially in the industrial and energy sectors, such as green energy production and networks, green renovation for buildings, etc.

The Farm to Fork Strategy (part of the Green Deal) outlines multiple transformative changes of EU agriculture until 2030. The climate and sustainability dimension of the Farm to Fork Strategy is built upon several pillars, which together cover a large part of the food chain and production cycle: sustainable food production and processing, wholesale/retail markets, sustainable food consumption and healthy diets, food loss and waste. The Farm to Fork Strategy has the aim of European food production becoming the global standard for sustainability and aims to enhance opportunities for all operators in the food value chain and support introduction of new technologies and scientific discoveries, and to combine these with increasing public awareness and demand for sustainable food (but see critique in Bremmer *et al.* 2021). It focuses on tools such as regulation (labelling, prohibitions, restrictions) on the one hand and broad research programmes such as Horizon Europe on the other, to initiate and accelerate changes in EU agriculture. The EU Biodiversity Strategy is closely linked to the Farm to Fork Strategy and was published simultaneously. The two strategies have several overlapping goals and targets, for example, taken together they aim to bring a diverse and resilient nature back to agricultural landscapes (as well as to forests, seas, coasts and urban areas). There is a strong consensus among EU member states about the importance of reaching these goals, but the challenge is to find mechanisms for reaching them along many different and locally adapted pathways.

The Farm to Fork and Biodiversity Strategies include a range of ambitious targets intended to put the EU food system on a transformative path to greater sustainability. Those with the greatest relevance to agricultural production include the following:

- agriculture to contribute to a reduction of at least 55% in net Green House Gas (GHG) emissions by 2030;
- reduction by 50% of the use and risk of chemical pesticides, and reduction in use of more hazardous pesticides by 50% by 2030;
- reduction of nutrient losses by at least 50% while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilisers by at least 20% by 2030;
- reduction by 50% of sales of antimicrobials for farmed animals and in aquaculture by 2030;
- reaching 25% of agricultural land under organic farming by 2030;
- a minimum of 10% area under high-diversity landscape features.

The Commission has in parallel set out a new green architecture for the Common Agricultural Policy (CAP), featuring strengthened mandatory requirements and increased funding opportunities for green farming. Among the measures in the new CAP are the preservation of soils through requirements to protect carbon-rich wetlands and practice crop rotation, and an obligatory nutrient management tool designed to help farmers improve water quality and reduce ammonia and nitrous-oxide levels on their farms. A new stream of funding from the CAP's direct payments budget for 'eco-schemes' will support and incentivise farmers to undertake agricultural practices beneficial for climate, biodiversity, and the environment. The 'green direct payment' (or 'greening') supports farmers who adopt or maintain farming practices that help meet environmental and climate goals. Through greening, the EU aims to reward farmers for preserving natural resources and providing public goods that represent benefits to the public but are not reflected in market prices.

The question is whether these efforts in the CAP will be sufficient and whether other necessary areas of intervention, such as reducing food waste in the entire production and consumption chain and changes in consumers' diets, will be sufficiently integrated to enable the needed transformation of the entire food system within a decade's time.

2 Challenges in the global food system

2.1 The concept of the food system

Agricultural production systems in the world are currently severely threatening ecosystem resilience and climate stability, and they constitute a large driver of environmental degradation and transgression of planetary boundaries (Willett *et al.* 2019). For example, there are severe impacts through the loss of species biodiversity and ecosystem services such as pollination (Gossner *et al*. 2016; IPBES 2018), increase in soil erosion, declines in soil fertility, downstream damage to water resources and degradation of coastal ecosystems (Fader *et al.* 2013; Rist *et al.* 2014). Furthermore, it is estimated that food systems are responsible for 34% of global GHG emissions (Crippa *et al.* 2021), including 20% alone from animal-based foods (Xu *et al*. 2021).

An increased sustainability and resilience (see Box 1) of agricultural production in the face of these crises must be based on a systemic view that not only analyses how to mitigate the effects of the current multitude of global crises on agriculture, but also indicates what specific transformations are needed to reduce the contribution of agricultural production itself to these crises, and to increase the resilience of the food system (Queiroz *et al.* 2021).

The concept of the food system (Figures 1 and 2) refers to all the elements, activities, processes, and ecological and socio-economic outcomes that relate to the production and consumption of food (Box 2) (see also EASAC 2017a; EASAC and IAP 2021).

It is paramount to stress that the food system functions in a dynamic network of economic, social and political relations (the drivers: Figure 1), includes these, and is affected through interlinked (other) human activity systems. It follows that many of the failures ascribed to the food system – including hunger, food poverty,

Box 1 Definitions of key concepts used in the report

Sustainability. Manage all resources in ways that guarantee the wellbeing of current and future generations, ensuring distributional equity. Sustainability is a normative concept, representing the vision for society (Elmqvist *et al.* 2019).

Resilience. The capacity of a system to absorb disturbance, reorganise, maintain essentially the same functions and feedbacks over time and continue to develop along a particular trajectory. This capacity stems from the character, diversity, redundancies and interactions among and between the components involved in generating different functions. Resilience is fundamentally non-normative and an attribute of the system and applicable to different subsystems (Folke 2016).

Disturbance. An event that is relatively discrete in time and space and that disrupts the structure of an ecosystem, community, or population, and changes resource availability and/or the physical environment.

Adaptation. A process of adjusting in behaviour, physiology, or structure to become more suited to a changing environment.

Ecological restoration. The process of assisting the recovery of a degraded, damaged, or destroyed ecosystem to reflect values regarded as inherent in the ecosystem and to provide goods and services that people value (Martin 2017).

Natural regeneration. The capacity of ecosystems to recover spontaneously after the cessation of degradation via the natural recolonisation by plants and animals (Gann *et al.* 2019).

Nature-based solutions. Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits (Gann *et al.* 2019).

Box 2 The concept of the food system

'*A food system gathers all the elements (environment including all organism and people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes. Specific attention is paid to nutrition and health outcomes of food systems. There are three constituent elements of food systems, as entry and exit points for nutrition: food supply chains; food environments; and consumer behavior.*' Citation from HLPE (2017), p. 11.

'*Sustainable food systems embody qualities that support the six dimensions of food security. Sustainable food systems are: productive and prosperous (to ensure the availability of sufficient food); equitable and inclusive (to ensure access for all people to food and to livelihoods within that system); empowering and respectful (to ensure agency for all people and groups, including those who are most vulnerable and marginalized to make choices and exercise voice in shaping that system); resilient (to ensure stability in the face of shocks and crises); regenerative (to ensure sustainability in all its dimensions); and healthy and nutritious (to ensure nutrient uptake and utilization).*' Ibid, p. XV.

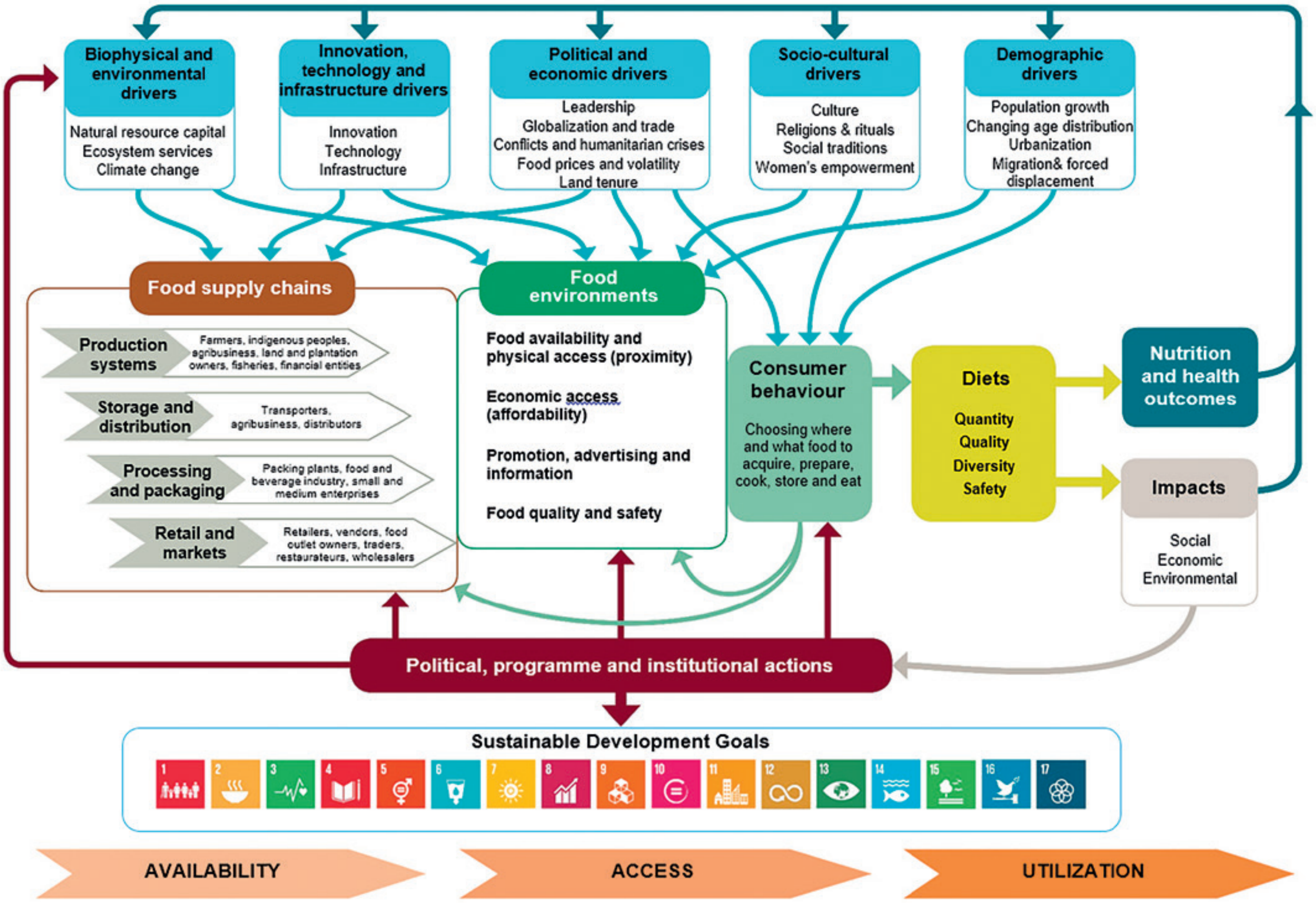

Figure 1 The food system as an integral part of the economic, political and social systems. Source: HLPE 2017. Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition (HLPE) of the Committee on World Food Security, Rome. http://www.fao.org/3/a-i7846e.pdf. Reproduced with permission.

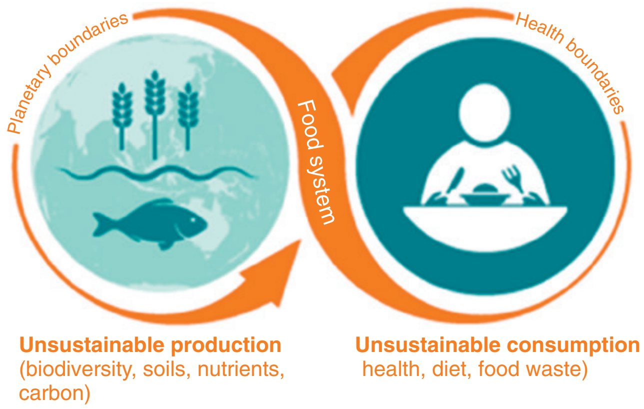

Figure 2 The multiple sustainability challenges in both production and consumption chains of the current food system. Regenerative agriculture is mainly addressing the left unsustainable production sphere, but is strongly influenced by dynamics in the unsustainable consumption sphere. Modified from EAT Lancet Commission Summary 2018.

poor labour relations, corporate dominance – will not be successfully addressed by action within the food system itself, but only through higher level political and economic change.

2.2 Global food system, production and trade

The consolidation and homogenisation of actors in the global food system has led to a decrease in the diversity of practices, food cultures and ways to produce and consume food, resulting in a gradual loss of response diversity (*sensu* Elmqvist *et al.* 2003) in different parts of the system (Hendrickson *et al*. 2015; Folke *et al.* 2019; Nyström *et al*. 2019). In global agriculture, crop portfolios have become more homogeneous in composition, shifting towards a globally standardised and increasingly animal-based food supply based on a few crop types such as maize and soybean, predominantly used for animal feed and wheat and rice, predominantly used for human consumption (Nyström *et al.* 2019), and concentrated to a few regions in the world (Figure 3).

Nearly one-quarter of all food produced for human consumption is traded internationally (D'Odorico *et al.* 2014; MacDonald *et al.* 2015), and over one billion people are consuming internationally traded products to cover their daily nutrition (Nyström *et al.* 2019). International trade accounts for 24% of all agricultural land (Weinzettel *et al.* 2013), 23% of all freshwater

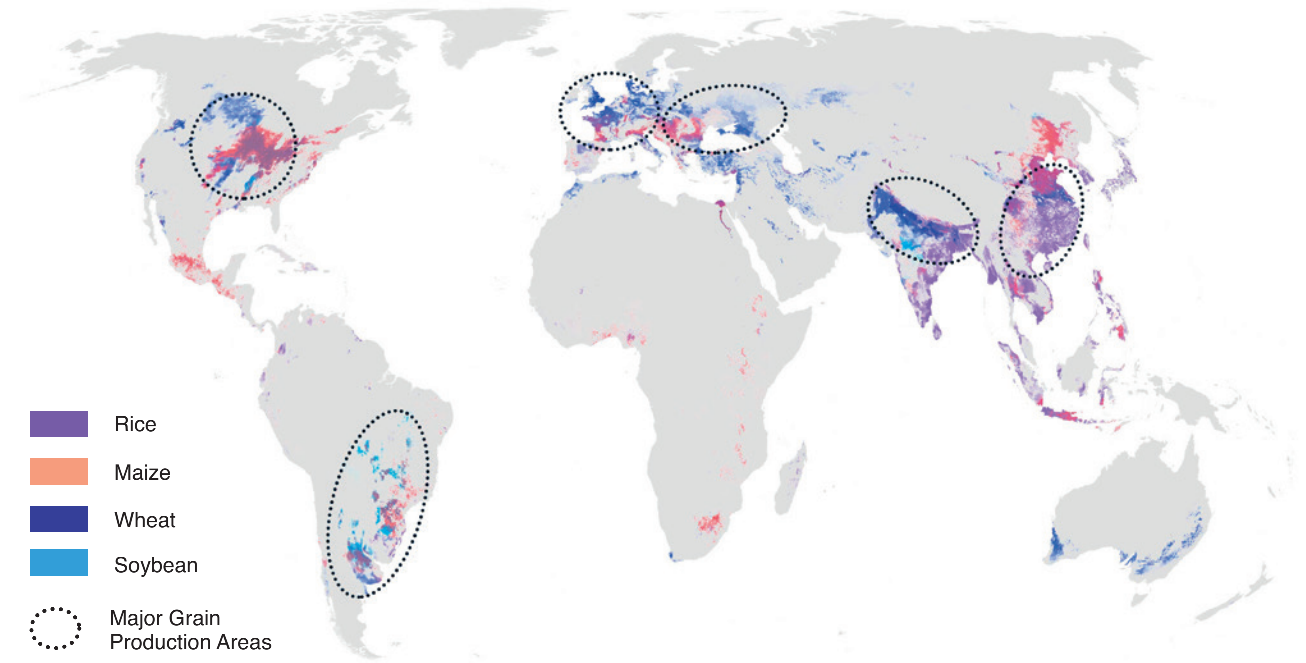

Figure 3 Global agricultural production of four major global grain staples is located in a limited number of regions of which Western and Central Europe is one. Source: McKinsey Global Institute 2020.

resources used for food production (D'Odorico *et al.* 2014) and more than 35% of global seafood production (FAO 2018). This wide international trade network results in a spatial decoupling which allows industries to substitute supplies from different species or production ecosystems so that global consumers remain relatively unaffected by, and unaware of, changes occurring at individual source areas (see discussion in Nyström *et al.* 2019). Trade thus, at least initially, provides response diversity (Kinnunen *et al.* 2020) that enables buffering against disruptions by providing alternative food sources, backup distribution, or emergency supplies. Over the past two decades, the number of regional trade agreements in force has more than tripled and Tu *et al.* (2019) suggested that the resilience of the global food system has declined over the past decades because of the trade-induced increased interconnectedness and reduced modularity. They argue that, owing to the structural characteristics of the food trade network, additional trade links may well further erode the resilience of the global food system. Indeed, despite efforts to maintain high and predictable yields, food production shocks have become more frequent over the past 50 years at a global scale, both on land and in the sea (Cottrell *et al.* 2019). The very same policies that increase national food security may therefore at the same time cause global food security crises (Nyström *et al.* 2019). Recently, such global-level disruptions were caused by, and experienced early in, the COVID-19 pandemic (Laborde *et al.* 2020).

Food and commodity trade has increased supply diversity to the majority of human populations (Kummu *et al.* 2020). However, when moving from the local scale with increased diversity, the global scale is characterised by an increasing trend of homogenisation and the risk of loss of resilience becomes even more obvious (Elmqvist *et al.* 2021). The economic logic of specialisation, and of increasing size of operations to reduce marginal costs and to gain comparative advantage in production, has resulted in an overall simplification of production systems within farms, and homogenisation of farming over landscapes and agroecological regions (Gosnell *et al.* 2019). Homogenisation of the food system, however, also provides potential entry points to influence the system. As Macfadyen *et al.* (2015) show, there are bottlenecks in the system, for example in food retailers. Thus, if a few key players can be convinced to modify behaviour/strategies they can influence the whole system from producers to consumers.

Homogenisation is also a concern from a biodiversity perspective. In industrialised countries, there is a trend away from mixed farming towards livestock production in 'factory farms' that depend on imported rather than self-grown feeds. Removal of livestock from the majority of farmland amplifies the trend of arable farmland simplification and is among the major causes of grassland homogenisation (see section 3.7), which is associated with loss of biodiversity.

In the global market, because of businesses' relentless search for comparative advantages, production of crop and livestock species gravitate to regions of highest productivities at large scales. The trade-driven breakdown of local and national farm-to-table links of increasingly urban populations has resulted in substantial impacts on regional and national production diversities (e.g. Elmqvist *et al.* 2021). Of importance is that there are parallel processes of both diversification and homogenisation of agricultural production within countries (Aguiar *et al.* 2020), and the recent discourse on localising food for dietary diversity and food system resilience is probably based on a yet incomplete understanding of the dynamics of food and production systems (see section 4.3.5). However, it is very clear that the trend of uniformity of diets towards a 'global diet' drives export-oriented agribusinesses towards simplification, monocultures, and homogenisation of agricultural landscapes and farming systems.

3 Challenges and opportunities in European agriculture

3.1 Challenges and opportunities to capture and store carbon and enhance biodiversity: the need for large-scale ecological restoration

One major challenge in Europe and elsewhere during the next decade is to transform management of landscapes to dramatically increase their carbon-storage capacities and regulate GHG emissions, so as to avoid the catastrophic effects of warming the planet by more than 2 °C, and to simultaneously reverse the current loss of biodiversity. Together, ocean and land ecosystems remove around 50% of anthropogenic carbon dioxide (CO_2) emissions from the atmosphere each year, with agricultural landscapes contributing with about 0.6 gigatonnes of carbon per year mostly by grasslands and 0.1 gigatonnes of carbon by peatlands per year (Friedlingstein *et al.* 2020). However, restoration of ecosystems on an unprecedented scale represents a large untapped potential for increasing carbon storage and is increasingly highlighted as one of the most important strategies to keep temperature rise below 2 °C (Morecroft *et al.* 2019). Strassburg *et al.* (2020) estimated that restoring 15% of converted lands in specific priority areas could sequester 299 gigatonnes of CO_2 – 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution – and at the same time contribute to reduce the rate of extinction of species.

In European agriculture, emissions of CO_2 come mainly from land conversion and use of organic soils (peat) for farming, while other GHGs such as nitrous oxide (N_2O) and methane (CH_4) are emitted mostly by soils, fertilisers and livestock (ruminants), respectively. Approximately 70% of agriculture-related GHG emissions in Europe comes from the animal sector (Leip *et al.* 2010). However, it is important to note that EU agriculture only accounts for 10% of total European GHG emissions (Mielcarek-Bocheńska and Wojciech 2021) and 11% of global agricultural GHG emissions (also including nitrification, denitrification and manure decomposition).

Because of its multiple benefits for carbon capture and storage and biodiversity, ecological restoration activities will receive large financial support from the Farm to Fork and Biodiversity Strategies. A significant proportion of the 25% of the EU budget dedicated to climate action is intended to contribute to ecological restoration and nature-based solutions. This large financial injection in ecosystem restoration enables actions that could serve multiple purposes, both for mitigation and adaptation. Globally, The United Nations has declared 2021–2030 the 'UN Decade on Ecosystem Restoration', and the Bonn Challenge and the New York Declaration on Forests aim to restore 350 million hectares of degraded ecosystems worldwide by 2030 (see also Dudley *et al.* 2021). In a recent study, the World Resources Institute found that the largest potential contributions to carbon reduction in the agricultural sector comes from ecological restoration, with dietary changes and reduction of food waste being the other main sources (Figure 4).

Yang *et al.* (2019) demonstrated that restoration of biodiversity on previously abandoned and degraded agricultural lands significantly increased carbon capture and storage. Grasslands are of particular interest, currently covering some 40% of the Earth's surface (White *et al.* 2000) and in Europe around 20%. Grasslands store approximately 34% of the global stock of carbon in terrestrial ecosystems, while forests store approximately 39% and agroecosystems approximately 17%. Unlike forests, where above-ground biomass is the primary source of carbon storage, most of the grassland carbon stocks are in the soil (White *et al.* 2000). Recent studies suggest that grasslands may have been underestimated in their capacity to capture and store carbon, at least in the short to medium term (one to three decades) compared with forested areas (Terrer *et al.* 2020). Numerous studies have found that elevated CO_2 results in much higher levels of soil organic carbon in grasslands compared with forests (reviewed in Terrer *et al.* 2020).

Anthropogenic grasslands and other open-land habitats are a characteristic of European landscapes that have continuously existed for millennia. They host many specialised species, and many are considered semi-natural habitats. Restoration initiatives for biodiversity purposes in Europe should therefore not only be focused on increasing forest cover, but also on restoring and maintaining open-land habitats, for example various forms of grassland and wetland (Tölgyesi *et al.* 2021). Depending on the landscape context, the size of the restored area and the rate of the degradation, there are a range of methods available for grassland restoration (Kiehl *et al.* 2010, Török *et al.* 2011). These range from supporting natural regeneration to many forms of assisted regeneration, such as seed sowing and plant material transfer (see section 4.3.3)

Investments in ecosystem restoration are well aligned with the concept of regenerative agriculture where restoration of eroded agricultural land is achieved through several approaches. Among these, crop rotations, agroforestry, reduced tillage, cover crops, organic amendments and vegetative filter strips are important. At a landscape scale, restoration would involve restoring landscape elements such as buffers,

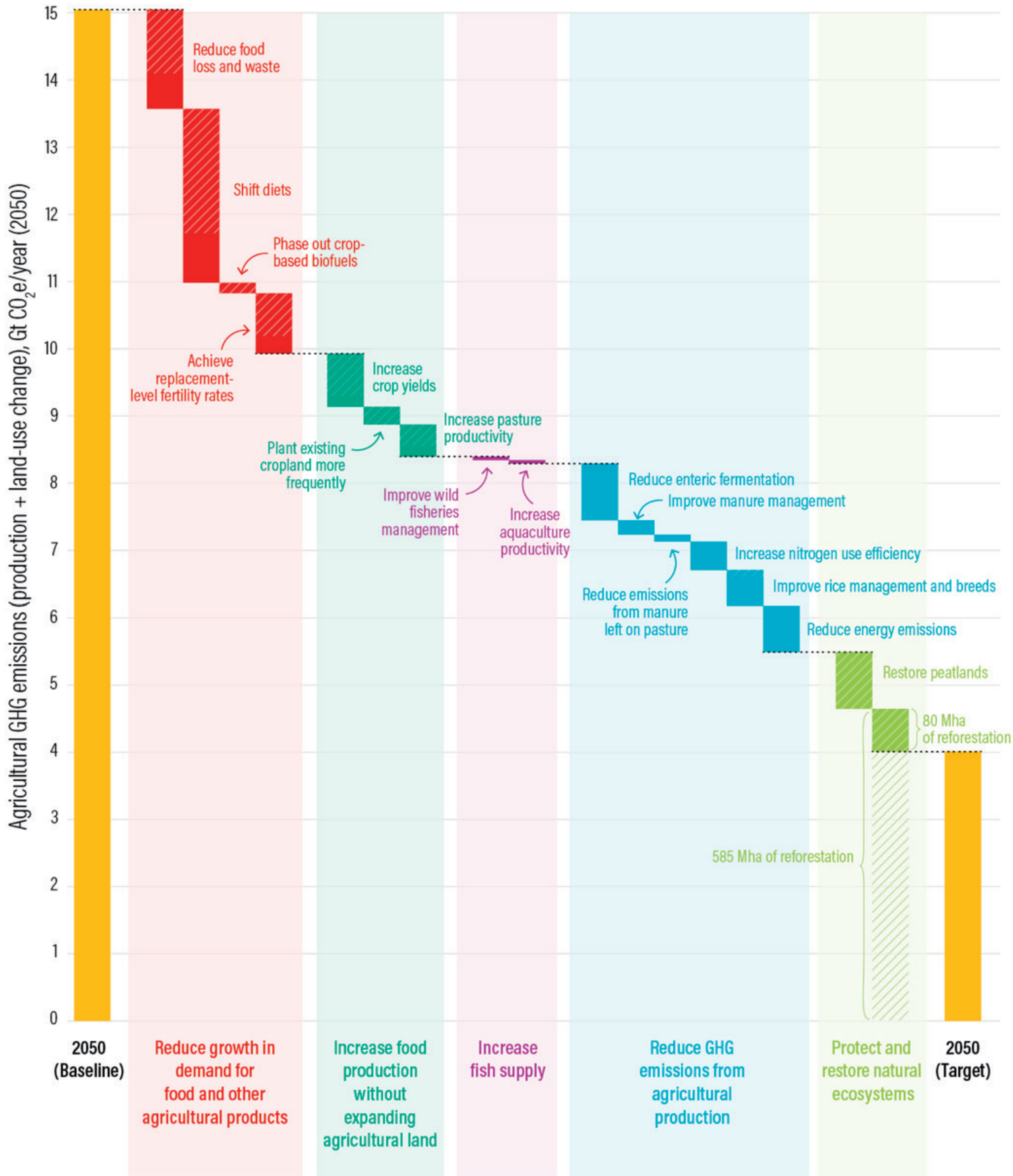

Figure 4 The potential of carbon reduction in the agricultural sector. Source: World Resources Institute 2018.

riparian corridors, hedgerows, permanent grasslands, etc. Such restoration may also decrease the necessity of pesticides in croplands and hence support the transition towards sustainable farming through increasing heterogeneity of monotonous agricultural landscapes, and through restoration of soil structure, particularly water-holding capacity. In the future, multiple challenges in the agricultural landscapes in Europe are linked to climate change effects on temperature and precipitation (e.g. IPCC 2021; and see section 3.2). These challenges should be considered in today's restoration planning, to restore ecosystems in ways that make them resilient to projected climatic changes.

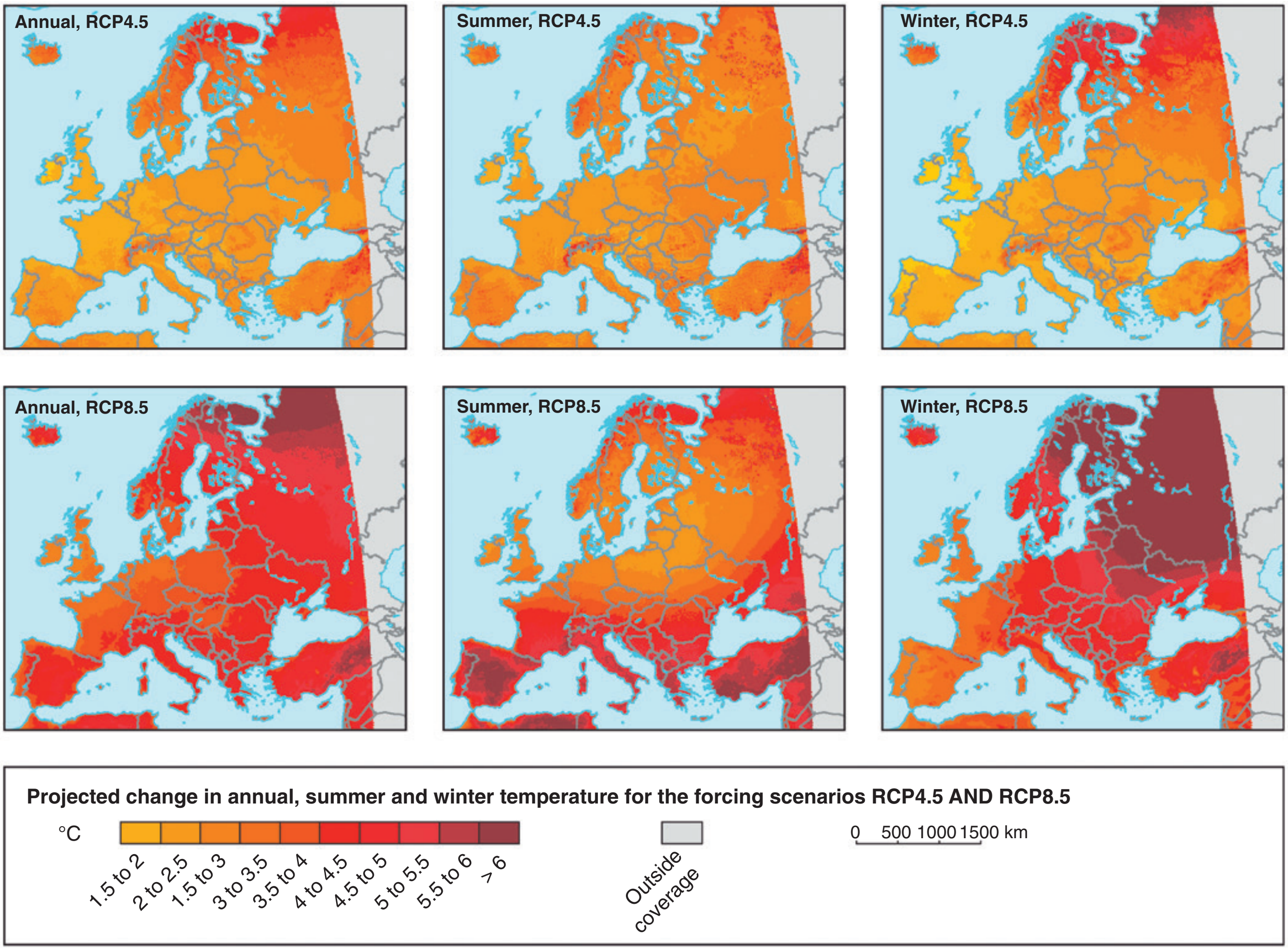

Figure 5 Projected changes in annual (left), summer (middle) and winter (right) near-surface air temperature (°C) in the period 2071-2100, compared with the baseline period 1971-2000 for the forcing scenarios RCP4.5 (top) and RCP8.5 (bottom). Model simulations are based on the multi-model ensemble average of regional climate model simulations from the EURO-CORDEX initiative (European Environment Agency (EEA) 2014, 2018: Projected changes in annual, summer and winter temperature, https://www.eea.europa.eu/data-and-maps/figures/projected-changes-in-annual-summer-1)

Overall, ecosystem restoration in the agricultural landscape represents a promising avenue to address the challenge of increasing carbon capture and storage and the enhancement of biodiversity. However, it is important to stress that there is a limit to how much carbon can be stored in the soil (see, for example, Guillaume *et al.* 2022) and we need more studies on how fast it can be stored. There is therefore still a strong need for developing and synthesising a robust evidence base to evaluate outcomes of restoration for informing and guiding sustainable policies.

3.2 Climate change challenges: projected impacts on European agriculture

In Europe, warming as a result of climate change is expected to be higher than the global mean temperature increase, especially in the north (Figure 5). Regional climate projections by CORDEX (Coordinated Regional Downscaling Experiment) for Europe at the Representative Concentration Pathway (RCP)8.5[1] emission scenario reveal that air temperature may rise between 4 and 6.5 °C, and that annual precipitation may decrease by more than 20% for many parts of Europe (Coppola *et al.* 2021) in the period 2071–2100, compared with the baseline period 1971–2000 (Figure 6).

3.2.1 Northern Europe

In northern Europe, climate change is expected to prolong the growing season by 1–3 months, mostly in higher altitudes and in the far north. Temperature is expected to increase between 3.3 and 6.4 °C for low

[1] Representative Concentration Pathway (RCP) is a GHG concentration (not emissions) trajectory adopted by the IPCC. In the RCP8.5 scenario, emissions continue to rise throughout the 21st century.

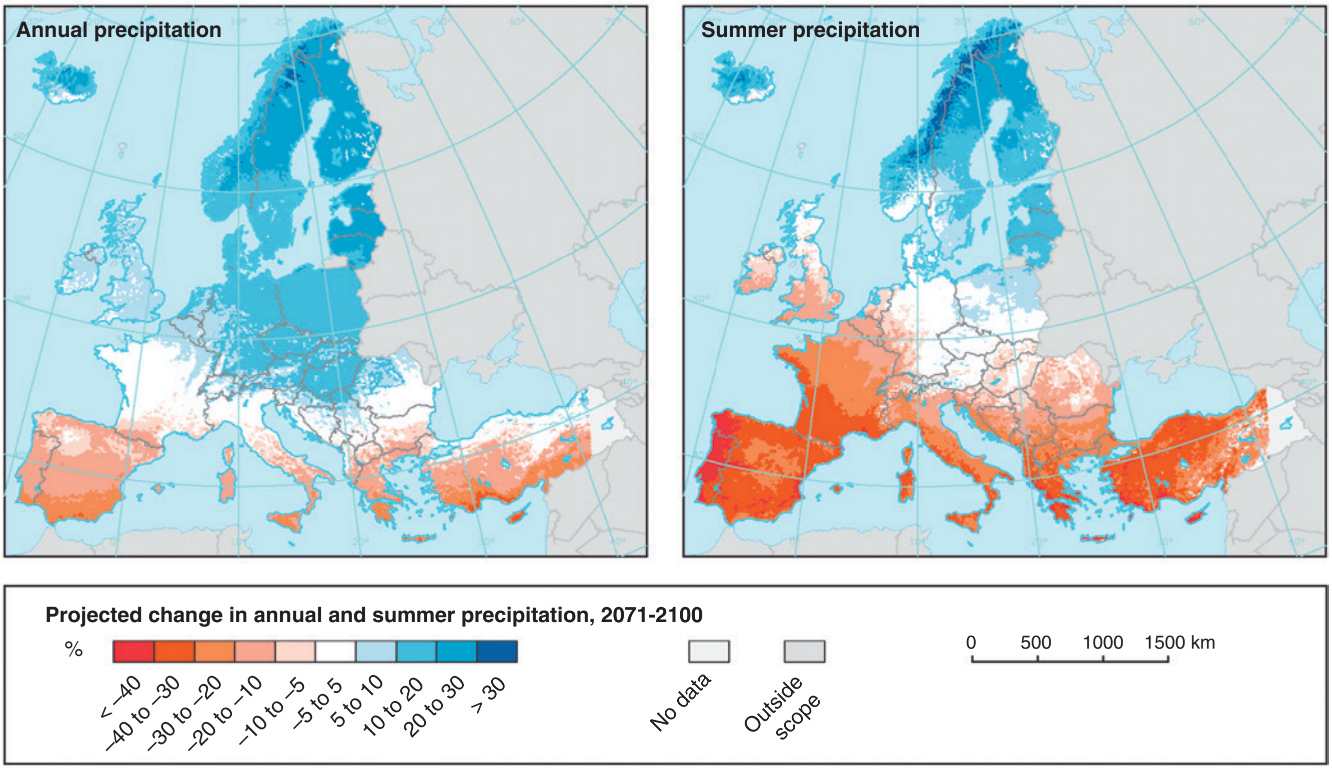

Figure 6 Projected changes in annual (left) and summer (right) precipitation (%) in the period 2071-2100 compared with the baseline period 1971-2000 for the forcing scenario RCP8.5. Model simulations are based on the multi-model ensemble average of regional climate model simulations from the EURO-CORDEX initiative. (European Environment Agency (EEA) 2019: Projected change in annual and summer precipitation, https://www.eea.europa.eu/data-and-maps/figures/projected-changes-in-annual-and-5.)

(RCP2.6) and high (RCP8.5) GHG emission trajectories, respectively, with vegetation zones extending northwards at a faster rate. Annual precipitation is expected to increase by 18% (variation between 7 and 23%), especially during autumn and winter. Seasonal changes are expected to vary even more. Unstable winter conditions with freezing and thawing can result in unexpected runoff conditions, affecting the winter survival of crops such as winter wheat and certain grasses (Hanssen-Bauer *et al*. 2015).

3.2.2 Central and Eastern Europe

In Central and Eastern Europe the mean annual temperature is projected to increase between 1 and 3 °C until the middle of the century and up to 5 °C by the end of the century (e.g. Giorgi *et al*. 2004). As a rule, in the autumn and winter months the temperature change in Central and Eastern Europe will be higher (up to 3 °C) compared with southern Europe (1-1.5 °C), and is expected to increase from the western coastal regions to the eastern continental interiors. Alternatively, the rise in summer temperature is expected to increase from the north to the south (van der Linden and Mitchell 2009). The projections for precipitation show a more complex picture. The spatial heterogeneity of precipitation is generally larger than that of temperature. In spring and autumn, the precipitation amount decreases in southern and southeast Europe.

In winter, central and southeast Europe show small changes in precipitation sums. Several climate change studies show a south–north contrast in precipitation, with an increase in northern Europe and a decrease in southern Europe (Christensen and Christensen 2007).

3.2.3 The Mediterranean

The Mediterranean Basin is expected to be more strongly affected by climate change, especially changes in precipitation, than other regions in Europe. There is strong evidence that the Mediterranean region has significantly warmed already (e.g. Lelieveld *et al*. 2012; Lionello *et al*. 2012). Multi-model sets of climate simulations show that widespread warming will continue in the Mediterranean during the 21st century. Over land, warming will probably be in the range of 0.9 to 1.5 °C or 3.7 to 5.6 °C during the 21st century, for low (RCP2.6) or high GHG emissions (RCP8.5), respectively (MedECC 2020). Future regional average warming will exceed the global mean value by 20% on an annual basis and by 50% in summer.

The sign and magnitude of observed land precipitation trends show pronounced spatial variability, depending on the time period and season considered. The most evident observed trend is a decrease in winter precipitation over the central and southern portions of the Mediterranean Basin since the second half of the 20th century (MedECC 2020). Models project a consistent decrease in precipitation during the 21st century for the entire basin during the warm season (April to September, with the highest magnitude in summer) and in winter for most of the Mediterranean, except for the northernmost regions, where wetter conditions are projected (Lionello and Scarascia 2018).

Desertification is the most important process of land degradation in arid, semi-arid and dry areas, which are prevailing in many agroecological systems of the Mediterranean region, resulting mainly from human impact. Desertification is driven by many factors such as erosion, salinisation, chemical pollutants, etc. (Kosmas *et al*. 2006). These drivers are affecting both natural systems and all types of agricultural ecosystem. Desertification is expected to be intensified by climate change (Le Houérou 1996; Webb *et al.* 2017).

3.2.4 Climate change and large-scale fires

With expected increased temperatures the risk of large landscape-scale fires will increase, as has already been observed in recent years, mostly in southern parts of Europe. Large-scale fires have a dramatic impact on biodiversity both above and below ground, as well as severely affecting local economies. In addition, and becoming increasingly serious, large-scale fires have a double impact on CO_2 emissions: fires destroy carbon capture and storage capacity and at the same time release large amounts of CO_2 into the atmosphere. The increasing risk of large-scale fires affecting both forested and agricultural landscapes may therefore jeopardise ambitious plans to use landscapes for the necessary massive increase in carbon capture and storage.

3.2.5 Agricultural production scenarios

The impacts of climate change on European agriculture in the middle and towards the end of this century have been assessed under different emission scenarios and regional meteorological models using either crop simulation models or compilations from the relevant literature (Figure 7).

Positive impacts on agricultural yields are predicted in northern and continental southern Europe, negative impacts in western and southern Europe, and few or negligible impacts in the continental north (Iglesias *et al.* 2009). According to recent studies (e.g. Hristov *et al.* 2020), grain maize is projected to be the crop most strongly affected by climate change in Europe. Under fully irrigated conditions, substantial yield reductions (–4 to –22%) are estimated for most producing countries, with more severe reductions in southern Europe in all scenarios. Under rainfed conditions, a collapse of the European maize production is projected for around 2050, with yield decreases greater than 23% in all EU countries and exceeding 80% in Portugal, Bulgaria, Greece and Spain. Wheat yields are expected to increase by 5–16% in central and northern Europe and decrease by 10–25% in southern Europe.

In northern Europe, a longer grazing season caused by climate change may be advantageous for ruminant production. On the other hand, open grasslands with appropriate fodder quality are rapidly disappearing in recent years because of shrub encroachment and afforestation (Dengler and Tischew 2018).

In Europe, agricultural production has been identified as the economic activity most sensitive to climate change impacts, especially in countries of the eastern Mediterranean. In general, a decline in yields has been predicted for many crops, the extent of which depends on local climate and management practices (see, for example, Giannakopoulos *et al*. 2009; Karamanos *et al*. 2011). It seems that climate change may positively affect cool-season C_3-crops (e.g. wheat, rye) owing to the predicted high CO_2 levels; C4-crops (e.g. maize and sorghum) may be affected negatively because their physiology is less responsive to a rise in CO_2 level. Cool-season crops could perform better in northern latitudes and higher altitudes; negative impacts are expected for warm-season vegetable and tree crops with high water requirements. It follows that the adoption and implementation of adaptation measures is a pivotal issue for facing the threats arising from the impacts of climate change and socio-economic factors on the food production system. This requires knowledge on the climate sensitivity of each crop, species and variety under different soil conditions (e.g. water retention, nutrients, organic matter and soil structure, among others), exposure to climate variables throughout the year (e.g. solar radiation, humidity, rainfall, temperature), interactions with other species (e.g. crops, biodiversity, pests), land uses, and the interdependency with the agricultural techniques used (Smit and Skinner 2002).

3.3 Challenges in the production chain: soils

Agricultural production is dependent on a multitude of factors, for example the genetics of the plants and animals, on environmental conditions, on agricultural practices, and importantly on soil. Soil fertility, organic matter turnover and renewal, water retention, physical structure and plant nutrient cycling are soil ecosystem services on which the growth of agricultural crops crucially depends. Notably, there are far fewer studies on soil structure and dynamics, in relation to various crops, than on the crops themselves (EASAC 2018). Although our knowledge has increased during recent decades, there is still a need for a strong research focus

Crop yield changes under the HadCM3/HIRHAM A2 scenario [%]

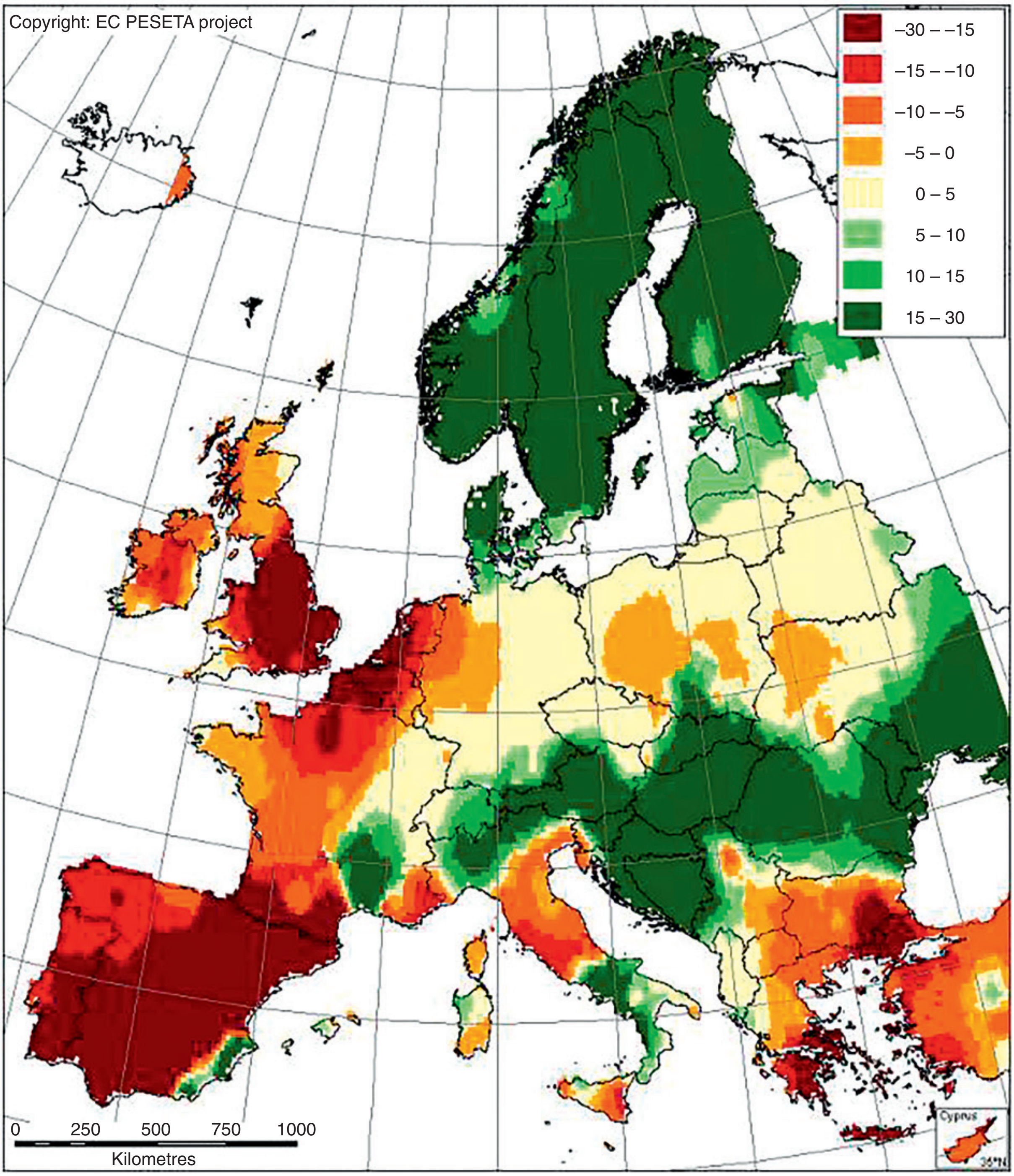

Figure 7 Simulated crop yield changes by 2080s relative to the period 1961–1990 according to a high emission scenario (IPCC A2) according to the HadCM3/HIRHAM model. European Commission (2019) PESETA I results — Impacts of climate change on agriculture (crop yields), https://ec.europa.eu/jrc/en/peseta/peseta-i-results/impacts-climate-change-agriculture-crop-yields, © European Union, 1995–2021.

on soils and particularly soil health (EASAC and IAP 2021). Among the soil degrading processes (decline in soil structure, compaction, salinisation, decline of soil biodiversity, acidification, etc.), soil erosion is the most well-known form. Soil erosion is a major factor in European agriculture: more than 12 million hectares of agricultural land in the EU (about 7.2% of the total) are estimated to be potentially severely eroded every year, and an annual crop productivity loss estimated to around €1.2 billion (Panagos *et al.* 2018). Here regenerative agriculture is important since it emphasises applying practices for restoring soil biodiversity and productivity. Promising new lines of research demonstrate the capacity of bacteria and fungi that promote plant growth to increase plant resistance to different abiotic stresses and to improve plant growth in degraded soils, such as high-salinity soils or on leached soils with low nutrient stocks and availability (EASAC 2018). This provides an exciting opportunity for the development of biological fertilisers to restore some crop cultivation on lands unsuitable for intensive agricultural practices.

Soils also play a key role in climate regulation. They contain two to three times as much carbon as the atmosphere (EASAC 2018) and have a capacity to capture carbon from the atmosphere through plant growth and long-term storage in soils. However, increasing soil carbon depends on local soil characteristics, nutrient availability and land use, so location-specific advice is necessary. It is also important to point out that there are clear limitations on how much carbon could be stored in soil (Guillaume *et al.* 2022).

Some soil types also contribute to carbon emissions. Organic soils (peatlands with >60% organic material, often located in previously drained areas) represent approximately 2% of EU soils, but were responsible for most agricultural land-use-based carbon emissions, while mineral soils have a net removal and storage of carbon (Figure 8).

Increasing soil carbon storage is not only a matter of adding more carbon to soils, but it is also important to keep carbon in the soil for extended time periods. The insights into soil carbon storage are currently undergoing a paradigm shift and there is an increasing understanding of the key role of microorganisms in stabilising carbon in soils for longer periods of time (Lehmann and Kleber 2015). Therefore, to manage soils well, the focus should not only be on increasing carbon stocks, but also on carbon retention times. This will also require constant careful management of soils since there is no one-time intervention that can improve carbon storage (Lehmann *et al.* 2020). Note that storing more carbon also requires that sufficient nitrogen is available (van Groenigen *et al.* 2017).

It is important to understand what organisms are doing as an integrated community of soil organisms: that is, the functional aspects of soil biodiversity and how functions such as nutrient and water retention, nutrient availability, and carbon storage may be maintained without too many external inputs. The interactions are complex, and the dynamic stability of soil functions (Moore *et al.* 2005) are vulnerable to the current trend of decline in biodiversity in intensively farmed soils across Europe (Tsiafouli *et al.* 2015). As already noted, fungi and bacteria play an important role, for example in transforming and recycling mineral and organic compounds of the soil. However, there is limited knowledge about mechanisms and how they are influenced by changing environmental conditions.

Climate change has both direct and indirect consequences for soils, as it changes soil biodiversity and biogeochemical cycles, and causes shifts in natural range limits of plant and animal species to higher latitudes and altitudes. These changes in species distribution drive changes in local habitat conditions, the composition of local vegetation and all organisms bound to the specific local conditions, and accordingly also changes in agricultural practices. Simultaneously, this may enhance the spread of invasive exotic plant and animal species and together have the potential to change local biodiversity, carbon stocks and nutrient cycles of soils, especially when agricultural and forestry practices are changing, ecosystems are colonised by species with novel traits or when diverse ecological communities become dominated by single species (FAO *et al*. 2020).

In developing sustainable agriculture, it seems obvious that the soil dimension of the agricultural ecosystems needs to be considered much more strongly (EASAC

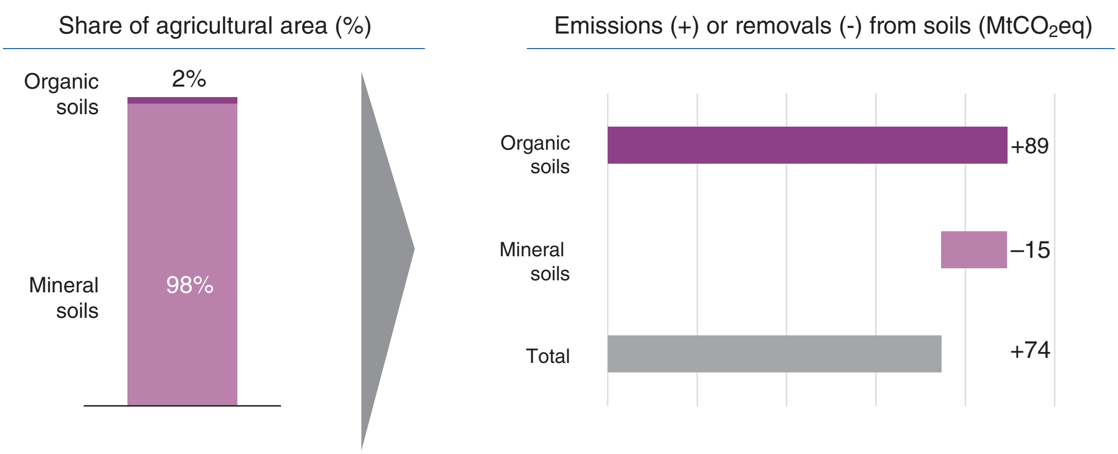

Figure 8 Mineral and organic soils in Europe and their contribution to carbon dynamics. Source: European Court of Auditors (2021).

2018; EASAC and IAP 2021). Existing data on agricultural land uses, which are produced at farm and field parcel levels for administrative uses and include details such as input intensities, should be used for assessing states and trends, at landscape and regional levels, of farming practices that drive changes in soil ecosystems. Flows and balances of plant nutrients should be monitored at landscape, regional, and national scales. This would also serve to advance nutrient recycling goals, as well as goals of protecting the wider environment from plant nutrient loading (e.g. OECD 2021).

3.4 Challenges in the production chain: water use

Water resources for agricultural production are unevenly distributed within Europe and globally. Food production covers 92% of blue water consumption (Hoekstra and Mekonnen 2012), and the gap between water needs and availabilities is widening with climate change. Agriculture affects both the quantity and the quality of water available for other uses and more than 30% of water use in Europe goes to the agricultural sector. In some parts of Europe, pollution from pesticides and fertilisers used in agriculture alone remain a major cause of poor water quality. One area where new practices and policies can make a significant difference in water efficiency gains is the irrigation of crops. In southern European countries such as Greece, Italy, Portugal, Cyprus, Spain and southern France, the arid or semi-arid conditions often necessitate the use of irrigation. In these areas, nearly 80% of total water consumption currently goes to irrigation. Climate change and changes in precipitation will provide challenges particularly so in the Mediterranean area and new measures for water management will be needed. For example, the use of treated wastewater for agriculture is already providing significant water management benefits in some European countries. Effective means of water saving is provided by deficit irrigation schemes (see, for example, Fereres and Soriano 2006; Mushtaq and Moghaddasi 2011), as well as the rationalisation of irrigation systems along the chain of water transport down to application practices.

This situation necessitates a water resource and use strategy for developing European farming and food system resilience in the global context. For example, water-intensive production could be strategically relocated to water-rich regions, as a strategy to relieve the unsustainable use of water for food production in water-limited regions (Chapagain *et al.* 2006; Lehikoinen *et al.* 2019). Such a strategy would slow the depletion of already endangered water sources, such as ground waters, rivers and wetlands, and it would help regenerate the associated ecosystems and their biodiversity. In regions with increasing risks of heavy precipitation, water retention in dams may represent effective ways to manage water flows and increase biodiversity in the landscape.

3.5 Challenges in the production chain: plant nutrients

Mineral fertilisers, in particular nitrogen (N) and phosphorus (P), are important nutrients absorbed from the soil by plants for their growth. However, a surplus of nitrogen and phosphorus has led to severe environmental pollution problems, particularly eutrophication of surface waters (Buckwell and Nadeau 2016). Environmental problems originating from nitrogen and phosphorus depositions are currently among the key challenges in a European agricultural context. Nitrogen is a particularly serious problem (EEA 2019), and multiple initiatives in several member states are under way to address this, for example in the Netherlands where agriculture is responsible for approximately 40% of the nitrogen emissions and a new law to limit nitrogen emissions recently has been adopted[2]. In contrast, deficiency of trace elements required for animal and human health is a serious problem in southern Europe with respect to both yield and nutrition quality of food crops (see, for example, López-Alonso 2012).

The 'green revolution' was characterised by a reorientation of agricultural practices towards a chemical–technical replacement of the ecosystem-based cycling of plant nutrients by inputs of mineral fertilisers, such as phosphorus from apatite rock and nitrogen from ammonium manufactured from natural gas. It is worth noting that in current European agriculture, the leakages and emissions to water, air and non-target ecosystems of the two key plant nutrients nitrogen and phosphorus equal the mineral fertiliser inputs of these nutrients (Table 1) (Buckwell and Nadeu 2016). This reflects the environmentally unsustainable organisation of plant nutrition in current agriculture.

One promising avenue to address this in most European farming systems is anaerobic digestion of manure and organic waste. This serves not only the recycling of nutrients, but also production of sustainable biogas (Koppelmäki *et al.* 2019, 2021a) to offset less sustainable fuels in farming and food processing. Such regenerative recycling capacity needs to cover the geographical scales from farm level to landscapes, nations, regions and the global scale, according to the principle of nested circularity (Koppelmäki *et al.* 2021b). Equally, biogas production is feasible for integrated bioenergy production and nutrient recycling for food

[2] https://www.dairyglobal.net/health-and-nutrition/nutrition/a-look-at-the-dutch-govs-new-law-to-reduce-nitrogen/

Table 1 Gross annual nutrient inputs to the EU27 agricultural systems and main output routes (years 2000, 2004, 2005), in million tons per year (Mt/yr). Source: Buckwell and Nadeau (2016), Table 4, p. 47.

Nutrient fluxes in the European agricultural system	Nitrogen (2000 & 2004)		Phosphorus (2005)	
	Mt/yr	%	Mt/yr	%
Nutrient inputs				
Mineral fertiliser	10.9	65	1.4	78
Imported feed	2.7	18	0.4	22
Other sources (N fixation, atm. deposition, soil)	3.1	17	?	?
Total nutrient inputs	16.7	100	>1.8	100
Nutrient destinations				
Food consumers	2-3		0.5	
Other uses	1-2			
Solid waste and sewage system	2-5		0.7	
Leakage to water, air and soil	11-12		1.3	
Consumer intake as % of total inputs		**~20**		**~30**

(All percentages are relative to net inputs.)

processing industries, other bio-based industries, and for municipalities (Feis *et al.* 2021).

3.6 Challenges in the production chain: pests and pesticides

The increasingly frequent use of pesticides to combat pests and pathogens is of growing concern across agricultural systems owing to the negative impacts on human health as well as on ecosystems (Sharma *et al.* 2019). It is now well recognised that chemical pesticides generate considerable losses in non-target species (see, for example, EASAC 2015) and cause widespread contamination of soil and water systems. Although these impacts are expected to worsen with expansion of agriculture and global climate change (Deutsch *et al.* 2018), emerging solutions may improve the sustainability and environmental outlook of pesticide usage. The most suitable strategy may be to modify or limit the usage of chemical pesticides by using a combination of sustainable alternatives to reduce crop vulnerability. For instance, employing gene-edited crops that are pathogen-resistant may reduce the need for pesticides. Another strategy may be to change the application technique of pesticides such as using a controlled release system (Singh *et al.* 2020). Such a strategy provides more precise control and monitoring of pesticide use and may help lessen the ecological burden of pesticides. Biopesticides and other nature-based solutions for biological control are also promising candidates to limit pesticide use. Considerable research has been conducted over the past decade to explore strategies such as the use of natural predators and parasites to reduce the burden of insecticides in crops. The goal of zero pesticide use is probably too ambitious and a limited and more targeted use more realistic.

3.7 Challenges in the production chain: use of animals

Ruminant livestock (e.g. cattle, sheep and goats) globally number more than 4 billion, have a total mass greater than that of all humans (de Tarso *et al.* 2016) and represent a significant source of GHG, mostly through emissions of methane (Meale *et al.* 2012). In the EU, there are currently 143 million pigs, 77 million bovine animals, 62 million sheep and 12 million goats (Eurostat 2019). Further, both ruminant and non-ruminant animals (e.g. pigs, horses and poultry) demand significant land and water resources: approximately 10% of global water is directly or indirectly used for livestock (Pulido *et al.* 2018). These negative processes are most typical of intensive animal farming systems, where domestic animals are kept indoors, and which are also responsible for a high rate of atmospheric nitrogen deposition and, in some instances, soil degradation. Livestock production contributes to carbon emission in several ways, including enteric fermentation, on-farm livestock rearing and manure management, fodder and feed production, and related land-use changes (Leip *et al.* 2010).

The net effect of grazing on the agroecosystems depend on grazing intensity, the animal type, habitat type and on many characteristics of the grazing regime, such as timing and duration (D'Ottavio *et al.* 2018; Bengtsson *et al.* 2019). Overgrazing is among the most important degradation factors for global rangelands, leading to soil erosion, desertification or aridification and the encroachment of rangeland weeds and several invasive species. In Europe, the regions most affected by overgrazing are parts of central, eastern and southern Europe (Török and Dengler 2018).

Most herbaceous vegetation was historically used as hay meadows and/or pastures across Europe, and many forests were cleared to form meadows, often with the help of fire (Pykäla 2001; Leuschner and Ellenberg 2017). Forest grazing by cattle was used for centuries in most parts of Europe (Pykäla 2001; Hejcman *et al.* 2013; Varga *et al.* 2020) and until the 19th century most of the lands in Europe were used for traditional animal husbandry (Pykäla 2001; Leuschner and Ellenberg 2017).

Today, extensive grazing and mowing systems play a central role in maintaining the open landscape structure and biodiversity of European semi-natural grasslands (Dengler *et al.* 2014; Tälle *et al.* 2016; Valkó *et al.* 2018). There are a total of 63 European Natura 2000 habitat types of community interest (European Commission 1992) that depend on low-intensity agricultural practices such as grazing or mowing (Halada *et al.* 2011). Semi-natural grasslands have been created and maintained by century-long human land use (Pykäla 2001; Dengler *et al*. 2014; Leuschner and Ellenberg 2017) and include the world records of diversity of small vascular plant species (Wilson *et al*. 2012; Chytrý *et al*. 2015). The main difference between historical versus current effects of grazing is not the type, anatomy or physiology of grazing animals (cattle, horses, sheep, goats, etc.); rather, it lies in the management of grazing (Teague and Kreuter 2020). Grazing is most often managed by economic considerations only, which often results in increased direct grazing pressure by large numbers of livestock in small areas or increased reliance on external input such as livestock feed and forage grown elsewhere.

The number of domestic herbivores grazing in European landscapes has declined by more than 90% during the past 100 years (Hobohm *et al.* 2021), having been replaced by indoor housing systems. However, pasture-based animal production remains important particularly in mountainous areas, and domestic herbivores play a central role in the management and conservation of particularly valuable High Nature Value (HNV) farmland. Approximately 30% of the agricultural land in the EU is managed under HNV farming (Keenleyside *et al.* 2014) but CAP support for the 'Management of landscape, pastures and HNV' covers only 8% of the utilised agricultural area (Strohbah *et al.* 2015). Farming systems in these areas have productive, environmental and societal functions, and their multifunctional role should be recognised by society and policy-makers. However, extensive grazing systems have generally declined in most parts of the EU, with the exception of, for example, Ireland, where the share of this land-use type has been consistently high in past decades (Beaufoy 2017). The general decline is driven by two major processes: abandonment and intensification. In past decades, mainly because of rural depopulation trends and insufficient funds for small farmers, extensively grazing livestock numbers decreased throughout Europe. The reduction was greatest in Central and Eastern Europe after switching from a state to a market economy in 1989, here livestock numbers have generally decreased by 50–70% (Isselstein *et al.* 2005). This had a key impact on semi-natural grasslands: large areas of former pastures and hay meadows were abandoned, resulting in the loss of biodiversity. In many sites where management of semi-natural grasslands ceased, grasslands either developed into shrublands or forests through natural succession. For example, 59–94% of the alvar grasslands in Estonia have developed into secondary shrublands and forests as a result of the declining dependence of animal husbandry on such semi-natural vegetation (Helm *et al.* 2006). Intensification of farming, such as increasing nitrogen inputs, agrochemicals, and increased land-use intensity, is also detrimental for species adapted to extensive management practices (Henle *et al.* 2008).

In Europe, intensification and abandonment of HNV farmland are reported as the main causes of biodiversity decline and conflicts between agriculture and biodiversity conservation (Henle *et al.* 2008).

3.8 Challenges in the consumption chain: health, nutrition, dietary change

The Farm to Fork Strategy argues that transition to sustainable agriculture will not happen without a shift in people's diets to become more plant based. Such a shift might be very challenging and more attention is needed to create an environment where sustainable choices are the most attractive ones as well as the most affordable, with sufficient information being provided to consumers on the benefits of alternatives (EASAC 2017a; SAPEA 2020: https://www.sapea.info/topics/sustainable-food/).

The Farm to Fork Strategy also recognises the inextricable links between healthy people, healthy societies and a healthy planet. It argues that the strategy brings a new comprehensive approach to how Europeans value food sustainability, and that it is an opportunity to improve lifestyles, health and the environment. The creation of a favourable food environment that makes it easier to choose healthy and sustainable diets will benefit consumers' health and quality of life, and reduce health-related costs for society. Indeed, health issues such as obesity still continue to rise, with over half of the adult European population being overweight, contributing to a high prevalence of diet-related diseases and related healthcare costs (EASAC 2017a). Overall, European diets are not in line with national dietary recommendations, and the 'food environment' does not ensure that the healthy option is always the easiest one.

There is currently no consensus about the degree of reduction of animal-source food to achieve environmentally sustainable diets. Some studies suggest that it would be best for the planet if we were to consume only plant-source foods, while others show that farm animals reared under a circular paradigm can play a crucial role in feeding humanity (see van Selm *et al.* 2022). Circular food systems aim to optimally utilise resources by prioritising arable land to produce plant biomass for human consumption and avoiding feed–food competition. Currently about 40% of our global arable land area is used to produce high-quality feed for farm animals, which to a large extent is human-edible. From a resource-efficiency point of view, farm animals could instead be fed what is considered non-human resources such as certain fractions of food waste and grassland resources.

Furthermore, human health cannot be dealt with separately from environmental and animal health, i.e. the safeguarding of healthy ecosystems (EASAC 2017a; EASAC and IAP 2021). A reflection on the 'One Health' approach needs to be initiated in EU policy-making. 'One Health' is the understanding that the health of humans, animals and the ecosystems they share are inexorably linked and interdependent. The COVID-19 outbreak offered an opportunity for reflection on the importance of resilience in emergencies. Sustainable and healthy diets for all were shown, during the pandemic, to depend much more on social and economic conditions than on technical aspects of food production and processing (Bisoffi *et al.* 2021) and demonstrated that diversity is a key component in the biophysical sphere as well as in the social sphere: new business models, new knowledge-sharing networks, new markets.

In practice, this would require a thorough review of all EU policies to ensure that they do not harm human or animal health, and the sustainable management of both production systems and natural ecosystems.

4 Regenerative agriculture: contribution to carbon storage, enhancing biodiversity and food production in European agriculture

4.1 What is regenerative agriculture?

Although the concept of regenerative agriculture was developed in the 1970s, there is still no consensus definition (Newton *et al.* 2020; Giller *et al.* 2021); and although regenerative agriculture is gaining increasing international interest, a critical scientific evaluation of objectives and assumptions has yet to be made (Giller *et al.* 2021). Furthermore, there is a multitude of other concepts that also relate to sustainable agriculture: for example agroecology, conservation farming, organic farming, ecological intensification and carbon farming, among others (see recent review by Oberč and Arroyo Schnell 2020). Regenerative agriculture, as defined in Oberč and Arroyo Schnell (2020), addresses similar objectives as many of the other above-mentioned concepts and approaches: maintaining agricultural productivity, increasing biodiversity and enhancing ecosystem services including carbon capture and storage. In contrast to other related concepts, regenerative agriculture is not viewed as defined *a priori* by a given set of rules and practices; instead, the goals that should be achieved are set and then practices and new technologies are adopted over time which contribute to achieve these goals. Regenerative agriculture explicitly stresses the opportunities of restoration, especially for soils in the agricultural landscape and the interplay in the production chain of various crops and ruminant and non-ruminant farm animals. These are principles also found in agroecology and organic agriculture. The concept is nonetheless viewed as broader and less prescriptive than other related concepts. Therefore, in contrast to some of the other approaches, regenerative agriculture does not exclude the use of, for example, modern plant and animal breeding technology, tilling, use of inorganic fertilisers or pesticides, but instead aims for a limited and more targeted use. A characteristic feature that regenerative agriculture shares with other concepts is that it aims to go beyond just reducing negative environmental effects of agriculture to actually producing positive environmental externalities (Oberč and Arroyo Schnell 2020).

Giller *et al.* (2021) pointed out that regenerative agriculture may have many components but the two main characteristic features are the following:

1. Restoration particularly of soil health, including increasing the capacity to capture and storage of carbon to mitigate climate change.

2. Reversal of biodiversity loss.

These are the two main components of regenerative agriculture that will be the focus of this report. In Table 2, we list several practices that are often included in regenerative agriculture and claimed either to contribute to carbon capture and storage and/or to enhance biodiversity in the agricultural landscape.

The Farm to Fork Strategy states that climate actions need to include investments in keeping existing carbon in the ground and promote a substantially increased capacity to capture and store carbon as well as reduce emissions of methane and nitrogen-containing GHG. This can potentially be accomplished through the application of several of the management practices listed in Table 2, such as making sure the soil is covered by plants all year round, using perennial crops, cover crops, adding crop residues such as mulch and straw or compost, and using minimum or no tillage. At the same time, to meet the goals set out in the Biodiversity Strategy, it is essential to consider how carbon capture and storage and biodiversity may simultaneously be affected when implementing a specific practice. This is because trade-offs can result in unwanted declines in one or the other target, as well as in other ecosystem services (Bennett *et al.* 2009) with the outcome dependent on the spatial scales on which services are generated (Lindborg *et al.* 2017). For example, trade-offs between functions related to plant production, carbon and nutrient cycling, and biodiversity have been demonstrated (Vazquez *et al.* 2021). Therefore, in the next sections we present an analysis of a large body of recent literature[3] of how different regenerative agricultural practices (Table 2) may result in either synergies or trade-offs between carbon capture and storage on the one hand and maintaining/enriching biodiversity on the other. To the extent that data are available, we also include evaluations of the impact of different practices listed in Table 2 on food production.

[3] The methodology for the literature review is described in Appendix 2.

Table 2 List of field- to farm-scale agricultural practices suggested in the literature to be part of regenerative agriculture. Note that many of these practices are also considered to be part of, for example, organic farming practices and agroecology. The table summarises the practices for which evidence has been gathered (see Appendix 2 for method description). The chosen practices are based on Oberč and Arroyo Schnell (2020); see also Newton *et al.* (2020) and Schreefel *et al.* (2020) and Giller *et al.* (2021). '(X)' denotes cases where there is no overall consensus or the effect is strongly context-dependent.

Farming practice	Suggested for carbon capture and storage	Suggested for biodiversity
Conversion of arable land to grassland	X	X
Grassland management (to capture carbon)	X	X
Woodland (wood pastures; silvo-pasture)	X	X
Native tree plantations on arable land	X	(X)
Agroforestry	X	X
Hedgerows, woody buffer strips, farmland trees	X	X
Improved crop rotations	X	
Crop diversity in rotations	X	X
Crop diversity — intercropping	X	(X)
Crop diversity — in sown/relay cropping	X	(X)
Minimise tillage: reduced, minimum or no tillage	X	X
Cover crops	X	
Retaining crop residues/Leaving crop residues on soil surface	X	
Organic amendments	X	(X)
Biochar	X	
Perennial crops	X	
Avoid insecticides, fungicides and herbicides	(X)	X
Field borders, etc. for beneficial insects (mainly pollinators and natural enemies to pests)	(X)	X
Flower strips (pollinators)		X
Buffer strips (often mandated for environmental/erosion reasons)	(X)	(X)
Herbal leys and summer fallows in crop rotations		X
Natural and semi-natural habitats		X
Landscape mosaics in space and time	(X)	X
Switch from large- to small-scale landscape patterns, e.g. decreased field size	(X)	X
Supporting transitional habitats, reducing sharp boundary structures		X

4.2 Regenerative agriculture and carbon capture and storage, biodiversity and food production

4.2.1 Effects of practices on carbon capture and storage

There are several practices for which there is good evidence for their positive effects on carbon capture and storage from meta-analyses and in several cases meta-meta-analyses (for full list see Appendix 3a). Some effects are quite large, such as agroforestry practices and conversion to grasslands, but most of the effects are rather moderate, of the order of 5–10%, and include practices such as increased diversity in crop rotations, the use of cover crops, and intercropping (although the positive effects vary with which crops species are included) (Appendix 3a). Reduced or no tillage also usually increases carbon capture and storage in the upper soil layers, although the effects on total carbon storage, if any, are still unclear. Retaining crop residues enhances carbon capture and storage on irrigated land, although the effect varies with soil type. Perennial crops in crop rotations also increase carbon capture and storage, as does addition of biochar (see Appendix 3a).

It is clear that only more drastic changes in agricultural land use can bring about larger increases in carbon capture and storage. Examples are conversion of arable land to grasslands and changing to agroforestry systems (Figure 9). The largest positive effects of agroforestry

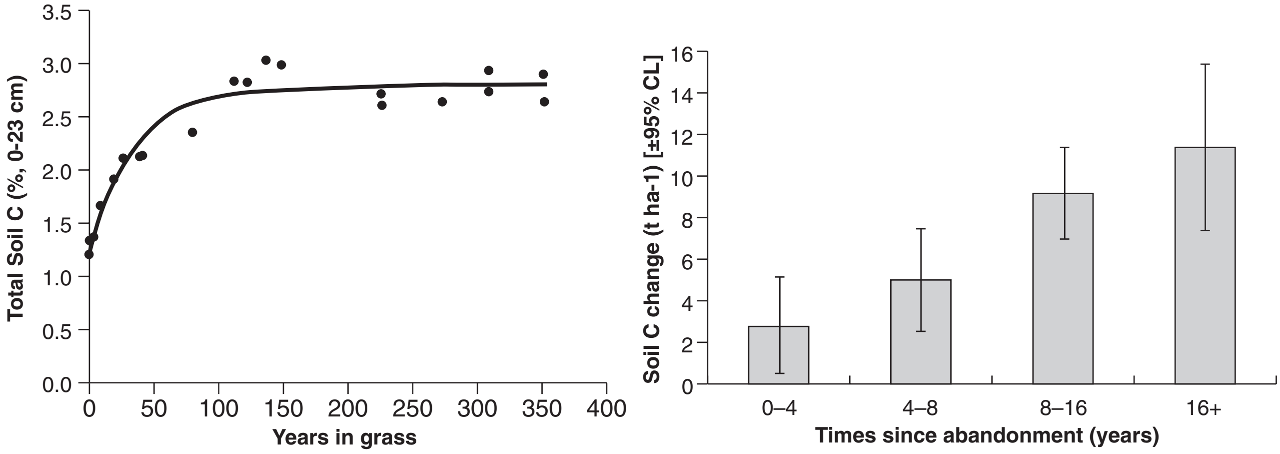

Figure 9 Time frames for carbon capture and storage (increase in organic carbon) by conversion of arable land to grasslands. (a) Data from Rothamsted, UK (Smith 2014, Fig. 1). (b) Soil carbon change on abandoned temperate agricultural soils (figure drawn based on data from meta-analysis in Kämpf et al. 2016, Table A1).

are, however, mostly found in tropical, subtropical and Mediterranean areas, while effects are less clear in western and northern European agricultural systems. Edge zones such as hedgerows, farmland trees and woody buffer strips increase soil carbon, but the areal extent of such edge habitats may be rather small in many agricultural landscapes. For example, hedgerows showed a 3% increase in carbon capture (Beillouin *et al.* 2021). In contrast to edge zones and flower strips, restoring previously drained wetlands will in most cases significantly increase carbon capture and storage (e.g. Moreno-Mateos *et al.* 2012) (see Appendix 3a).

It has been argued that the most important practice for carbon capture and storage in the agricultural landscape is to keep the land green, i.e. covered by plants during all seasons (Professor T. Kätterer, Swedish University of Agricultural Sciences, Sweden, personal communication, summarising updated knowledge in late 2021). Although this has not been subject to extensive evidence-based reviews, it is largely compatible with other evidence on cropping practices, such as the application of cover crops, reduced tillage and conversion to grasslands (see, for example, Kämpf *et al.* 2016; Haddaway *et al.* 2018; Li *et al.* 2020; Beillouin *et al.* 2021; see also Keel *et al.* 2019).

4.2.2 Effects of land use and practices on biodiversity

Conversion of arable land to grasslands is likely to increase biodiversity, although the timeframe for such positive effects may be quite long, at least of the order of 10–15 years (SER 2002). The effects will also vary a lot depending on restoration management and past land use (Bullock *et al.* 2020). Afforestation of permanent and semi-natural grasslands is highly negative for grasslands with high diversity, and should be avoided (see Queiroz *et al.* 2014; Tölgyesi *et al.* 2021). The evidence for long-term increases of biodiversity after conversion from arable to grasslands exists (e.g. Sexton and Emery 2020), but synthesis is compromised by the relative scarcity of long-term monitoring studies with appropriate controls (but see, for example, Nerlekar and Veldman 2020). Reduced tillage practices seem to have mixed effects on soil biodiversity and ecosystem services, but this may require more studies since the effects vary, not only across organism groups but also among soils, regions and details of other management practices (Appendix 3b).

Here we review the effects of land use and practices on multiple components of agrobiodiversity on the farm scale, from within-crop diversity to the diversity of crop species and crop cultivation practices. We also evaluate the effects on carbon capture and storage and soils.

4.2.2.1 Within-crop diversity, use of landraces

Within-crop genetic diversity is an important component of agrobiodiversity (Negri *et al.* 2009) that is also acknowledged in the EU Biodiversity Strategy. The conservation of crop genetic diversity was the objective of Aichi Target 13 of the UN Convention on Biological Diversity, which has not been sufficiently addressed in the EU so far. Landraces are ancient local crop types that are still in a constant state of evolution; using modern selection and breeding technology tools to shape these preserved landraces is a further step in their evolution to preserve their agricultural significance (Casañas *et al.* 2017). Under modern agricultural conditions, using ancient landraces is a challenge but also an opportunity. Landraces can be included in highly sustainable agronomic models with low-input requirements. They can increase the resilience of crop production if they have better adaptation to changing climate and resistance to pests than modern cultivars (see Negri *et al.* 2009). They also represent an important part of cultural heritage. Landraces are vanishing at an increasing rate; thus, urgent action is required to inventory, rescue and preserve the wealth of European landrace diversity (Negri *et al.* 2009), as well as the cropping systems that maintain and develop them over time.

Within-crop genetic diversity can be increased by using variety mixtures instead of monocultures (Wuest *et al.* 2021). Variety mixtures can provide several agricultural and environmental benefits: they can decrease the spread of pathogens and can increase the stability of the production and the provision of ecosystem services within a field, particularly in view of expected climate change effects (see section 4.5). When designing the proper crop variety mixtures, it can be helpful to consider the ecological mechanisms leading to a positive relationship between biodiversity and ecosystem functioning, and its stability through time (Barot *et al.* 2017). Even though crop variety mixtures can have several benefits, there are several challenges related to their application, such as potentially undesired trait heterogeneity and uncertainties about performance of mixtures (Wuest *et al.* 2021).

4.2.2.2 Diversification of crop plants and crop cultivation practices

Crop diversification evolved over time in areas of subsistence agriculture as a necessary response to climate variation and different kinds of pest outbreak. Intensification of agriculture has eroded this capacity but in recent times crop diversification measures have been re-emerging (Lin 2011; Marini *et al.* 2020; Tamburini *et al*. 2020; Beillouin *et al*. 2021). Crop diversification is a hot topic in agroecological research: 95 published meta-analyses on crop diversification were identified by Beillouin *et al.* (2021). This analysis integrated 5156 experiments on 120 crop species in 85 countries. Surprisingly, Europe, especially eastern and central–eastern Europe, is understudied; 76% of studies on crop diversification were found to be from outside Europe (Hufnagel *et al.* 2020).

The global meta-analysis of Beillouin *et al.* (2021) showed that crop diversification enhanced crop production (+14%), biodiversity of non-cultivated plants and animals (+24%), and several ecosystem services including water quality (+51%), pest and disease control (+63%) and soil quality (+11%) (Figure 10). Having a variety of different crops engenders a greater ability to suppress pest outbreaks and dampen pathogen transmission, which may worsen under future climate scenarios, as well as to buffer crop production from the effects of greater climate variability and extreme events. Systems with low inputs of inorganic fertilisers, pesticides and herbicides, such as organic farming, have been developed using complex crop rotations that allow handling of weeds, pests and input of nutrients, especially nitrogen, and are often quite successful (see, for example, Chongtham *et al.* 2017; Nkurunzisa *et al.* 2017).

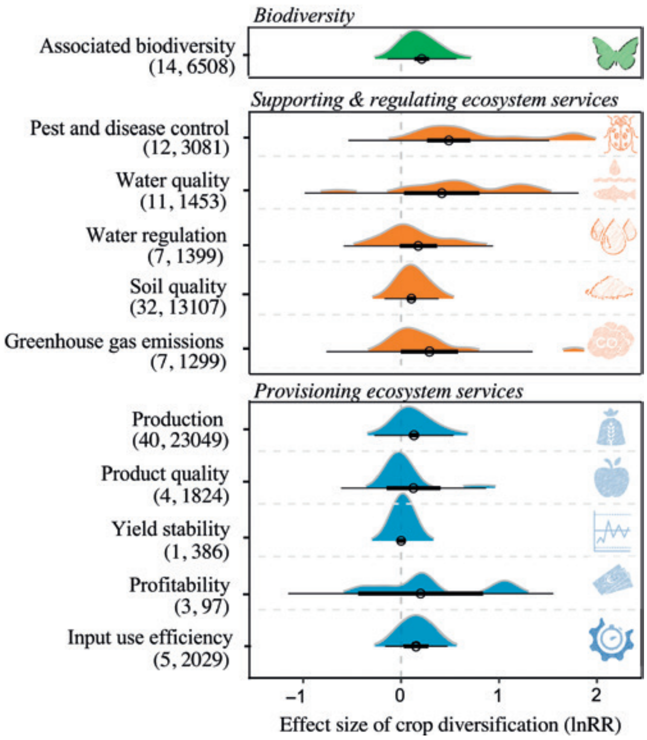

Figure 10 Summary of the evidence on the effect of crop diversification practices on biodiversity and ecosystem service. Source: Beillouin et al. 2021.

Increasing diversity of crops in rotation (spatial and temporal plant diversity) had a positive effect on soil microbial diversity and richness; this effect was true predominantly for total (fungal, bacterial and archaeal) free-living microorganisms in the bulk soil; and positive relationships between above- and below-ground biodiversity were confirmed (Venter *et al.* 2016). Research suggests that cropping systems diversification through intercropping can be used for simultaneous production of cereals and grain legumes, while increasing the use of nitrogen sources and reducing external inputs of nitrogen fertilisers, thereby enhancing agricultural sustainability (Rodriguez *et al.* 2020). Intercropped systems show positive effects on arthropod abundance, especially on pollinator diversity, while obtaining high yield (Brandmeier *et al*. 2021). A meta-analysis of intercropping systems showed that they can provide a win–win solution for increasing biocontrol services and yield at the same time (Iverson *et al.* 2014; see also Chunjie *et al.* 2020).

Crop rotations that included functionally diverse perennial crops or cover crops were the most effective at increasing carbon input and soil organic carbon concentrations relative to grain-only rotations; the effect was more pronounced in systems with low nitrogen inputs (King and Blesh 2018).

Temporal crop diversification was found to be more effective in suppressing weeds than increasing crop species richness alone (Weisberger *et al.* 2019). The combination of several crop diversification strategies can outperform any individual strategy (Beillouin *et al*. 2019): the combination of practices such as rotation extension, intercropping, multiple cropping or multi-service cover crops could improve the environmental performances while maintaining *a priori* economic and social performances at satisfactory levels (Viguier *et al.* 2021). Positive effects of crop diversification schemes on natural enemies were stronger in large-scale than in small-scale experiments. Also, yield reduction due to plant diversification was a strong outcome in small-scale (<250 m^2) but not large-scale experiments (Letourneau *et al.* 2011). Even though all recent syntheses agree that crop diversification can offer a win–win solution for supporting crop production, biodiversity and ecosystem services, there are still major knowledge gaps about water consumption, profitability, product quality and production stability in crop diversification systems (Beillouin *et al.* 2019), and there is a need to develop technology suitable for diversified production systems.

4.2.2.3 Meadows and pastures

Meadows and pastures of various kinds are still important components of many agricultural landscapes. Owing to agricultural intensification and rural depopulation, the area of extensively managed hay meadows and semi-natural pastures is declining in most regions and the extent of intensively managed silage fields and pastures is increasing (see section 3.7). Spatial and temporal diversification of these habitats in terms of their species composition and structure increases the local biodiversity and provision of ecosystem services (Bullock *et al.* 2006). Semi-natural grasslands are among Earth's most species-rich ecosystems and an important example of how long-lasting, low-intensity human activities may lead to an outstanding biodiversity (Wilson *et al.* 2012; Habel *et al.* 2013; Dengler *et al*. 2014). Along with climatic, topographic and edaphic conditions, management is a particularly important driver of plant species richness in semi-natural grasslands. Traditional, extensive management practices, such as grazing or mowing, usually support a high diversity, not only among plants (see, for example, Eriksson *et al*. 2002; Lindborg *et al*. 2008; van Swaay *et al*. 2013; Babai and Molnár 2014; Tälle *et al*. 2016). Abandonment of management usually leads to secondary succession towards shrubland or forest communities (Queiroz *et al*. 2014; Valkó *et al*. 2018), while intensification through excessive application of fertilisers, nutrient input by atmospheric deposition and from runoff water from surrounding areas, too frequent mowing, drainage, sowing of highly productive species of grasses and/or legumes, and too intensive grazing often lead to biodiversity decline (Bullock *et al*. 2020; Dengler *et al*. 2020). Consequently, diversification of grassland species composition can be best achieved through intermediate management intensity and adaptation of management plans to local habitat conditions. The use of forage legumes and herbs in temporal grassland swards is a promising strategy to enhance productivity and planned species diversity in forage-based, low-input dairy production (Lüscher *et al*. 2014; Hamacher *et al*. 2021). Structural diversification of grassland vegetation is usually beneficial for coexistence of multiple taxonomic groups and can be achieved by increasing structural heterogeneity within, around and between grassland habitats (Diacon-Bolli *et al.* 2012).

It is clear that large-scale intensification of agricultural practices reviewed in this chapter (homogenisation of within-crop diversity, crop monocultures and intensification of meadow and pasture management) is detrimental to biodiversity and ecosystem services at the landscape level (e.g. Tscharntke *et al.* 2021). This means that strategies for biodiversity conservation are largely dependent on management at scales larger than individual fields, i.e. measures that are coordinated at the landscape level and contribute to landscape diversity (see further in section 4.3.4).

4.2.3 Synergies between carbon capture and storage, biodiversity and crop production

Crop diversification practices, such as increased diversity in crop rotations, use of cover crops and intercropping, often show synergies with enriching biodiversity and increasing carbon capture and storage (Appendices 3 and 4; see also, for example, Aguilera *et al.* 2020; Tamburini *et al.* 2020). Importantly, Beillouin *et al.* (2021) also noted that such practices have positive effects on agricultural production, or at least no visible negative effects in the meta-analyses they examined (see also Tamburini *et al*. 2020). Diversification of agricultural practices can result in synergies for biodiversity, ecosystem services and crop production at multiple scales. Mixing crop varieties can help overcome trade-offs between soil fertility and yield compared with monocultures (Barot *et al*. 2017; Kiær *et al*. 2009). Intercropping systems with legume crops can increase the use of nitrogen sources and reduce external inputs of nitrogen fertilisers. Intercropping can provide higher and more stable yield, improved weed and pest control, increased soil stability and higher soil biodiversity than sole crops (Duchene *et al*. 2017). Well-designed polycultures can produce win–win outcomes between per-plant, and potentially per-unit area, primary crop yield and biocontrol (Iverson *et al*. 2014). This also seems to hold for agroforestry practices. Land-use change from arable land to grasslands increases carbon capture and storage as well as biodiversity. It is important here to make a distinction between effects on above-ground biodiversity and soil biodiversity, which may or may not be correlated. The larger positive effects as a result of land-use change from arable land to grasslands are not accompanied by the same positive effects on agricultural production and represent an important trade-off. Field borders, flower strips and trees in edge zones are also, in general, considered positive for biodiversity (e.g. Sexton and Emery 2020), although with more marginal effects on carbon capture and storage.

All this suggests that practices associated with regenerative agriculture such as crop diversification, agroforestry (in the broad sense), permanent habitats and trees in arable landscapes should be given considerably more attention. In addition, keeping the soil covered by plants over all seasons seems important and regionally adapted practices should be developed. Several such practices may have win–win solutions, although the effects might be minor to moderate according to regional differences in soils, environmental and climatic conditions, and management practices. Note that in some cases substantial trade-offs also may be generated: for example, increased carbon storage leading to increased N_2O emissions, reduced tilling and increased use of cover crops may increase demand for weed management, and measures to enhance biodiversity result in decreased food production. Therefore, the application of these practices also needs monitoring to make sure that details on management can be followed and outcomes enhanced.

4.2.4 Implications for soils in European agriculture

Regeneration of soil fertility often requires the use of organic fertilisers: these contain the needed plant nutrients in organic compounds, the decomposition of which feeds the soil organisms, improves soil organic matter, restores soil chemical and physical properties, increases soil carbon stock, and makes the nutrients available to crop plants (see Schreefel *et al.* 2020). Grass leys[4] in both animal and stockless farming are needed as an essential part of regenerative rotations (Johnston *et al*. 2009; Prade *et al*. 2017). In stockless farms, this can be achieved by growing multipurpose leys for soil conditioning, carbon capture, biological nitrogen fixation, integrated with anaerobic digestion of the harvest. Such regenerative systems, called agroecological symbioses (Helenius *et al*. 2020), can be optimised to avoid food-energy competition (Koppelmäki *et al*. 2021a).

In mixed farming, high rates of recycling of nutrients in organic forms can be achieved within the farming system, as the slurries and manures produced by animals contain the major share of nutrients taken up from the soils by the feed crops, while the animal products exported from the system represent only a relatively minor flow. On the other hand, many urban areas have a large surplus of nutrients (see, for example, Akram *et al*. 2019). Agricultural specialisation, urbanisation and the availability of synthetic fertilisers have all contributed to less efficient recycling in current food systems (Bouwman *et al*. 2013). In many cases, European animal farms have stocks that are too large relative to their farmland for feed production. To restore recycling functions, it is necessary either to balance stock size with farmland area, or to establish distributed networks of manure processing industries for production of transportable recycling fertilisers, which are returned to the farms from which the nutrients were exported in the form of feeds (Akram *et al*. 2019). In stockless farming and horticulture, the 'stock' are the consumers in the food chain. Here, regenerating the plant nutrients necessitates recycling from side-streams and waste flows throughout the food chains. There is an urgent need to develop technologies for recycling, including technology development for nutrient recovery from municipal wastes.

4.3 Regenerative agriculture at the landscape scale: diversification, restoration and localisation

While evaluating the concept of regenerative agriculture, we identified and discussed above several promising practices at the farm scale. However, regenerative agriculture as it is currently presented (Oberč and Arroyo Schnell 2020) does not explicitly address larger scales (landscape and regional) despite the fact that several processes, particularly for maintaining biodiversity, are operating at these larger scales. This is a clear weakness of the concept. We therefore used the same approach based on meta-analyses and systematic reviews to review the evidence base for processes operating at the landscape/regional scales (see Appendix 4). On the basis of the results, we aim to highlight possible avenues for the improvement of the concept of regenerative agriculture considering landscape- and larger-scale processes.

Multiple pressures on agroecosystems such as intensification and uniformisation of agricultural practices lead to homogenisation and the decrease of agrobiodiversity and related ecosystem services at the landscape level (Bommarco *et al.* 2013). In response to these pressures, several approaches and activities to diversify agricultural practices target the increase of different levels of agrobiodiversity. Agrobiodiversity includes both the farmed organisms and farming systems, namely the planned diversity (from the genetic diversity of farmed organisms, species diversity of crops, to diversity of land use systems) and unplanned

[4] Ley: a piece of land planted with grass, clover, etc., for a single season or a limited number of years, in contrast to permanent pasture.

or associated diversity (the diversity of farmland wildlife and habitat diversity generated by farming). From an economic viewpoint, benefits of diversifying agroecosystems are expected to be greatest where the aims are to sustainably intensify production while reducing conventional inputs, or to optimise both yields and ecosystem services (Bommarco *et al.* 2013; Isbell *et al*. 2017). Diversification of farming systems can decrease anthropogenic inputs and increase provision of supporting and regulating ecosystem services that can enable a sustainable ecological intensification (Bommarco *et al.* 2013).

It is important to differentiate between the effects of diversification measures at the site, farm, landscape and larger scales as different actions, responses and decision-making have different results on different levels. However, there is evidence that low-intensity practices at the field and farm levels can support ecosystem services at the landscape level. For example, decreasing the area of annual crops means lower insecticide inputs and less disturbance at the farm scale, which supports effective biological control by parasitoids at the landscape scale (Jonsson *et al.* 2012). Larger spatial scales are less frequently analysed, but Renard and Tilman (2019) showed that greater effective diversity of crops at the national level can increase temporal stability of total national harvest. van Noordwijk (2002) created a model (FALLOW) that enables upscaling the consequences of farm-level decisions to the landscape scale, using crop rotation as an example. Such models can be a useful tool for large-scale landscape planning.

However, maintaining or increasing biodiversity in agricultural landscapes may often imply trade-offs between food production and the provision of other ecosystem services; therefore it is crucial to identify the potential conflicts and synergies (Jackson *et al.* 2007).

Addressing all the challenges agriculture currently faces requires innovative landscape-scale farming systems that account for changing economic and environmental targets. These novel agricultural systems need to be recognised, accepted and promoted by all stakeholders, including local residents, and supported by public policies. Agroecosystems should be considered as social–ecological systems and alternative farming systems should be based on ecological principles while taking societal needs into account (Altieri 1989; Bretagnolle *et al.* 2019). This is an important principle of agroecology (Altieri 1989) and it is paramount that these dimensions are also thoroughly included in the concept of regenerative agriculture.

4.3.1 Diversification of farming systems and land-use types

The parallel existence of multiple farming systems (such as livestock breeding and crop production) in a region may be beneficial for biodiversity as different farming systems support different types of organism. The formerly pronounced regional differentiation in farming systems (e.g. lowland areas focusing on crop production and mountainous ones on livestock breeding; transhumance and migratory shepherding in areas with high mountains; rotational management between grassland and cropland; specific land-use traditions of particular ethnic groups) gradually disappeared from most of Europe. As a result of agricultural intensification and uniform economic incentives (e.g. uniform subsidy mechanisms acting throughout Europe as part of the CAP), the variability of farming approaches has recently declined. Diversification of farm sizes, cultivated products as well as spatial and temporal land-use patterns may help to increase the food self-sufficiency of the regions (Vicente-Vicente *et al*. 2021) as well as the overall diversity of agroecosystems and the whole landscape (Tews *et al.* 2004). An important step towards sustainability and resilience of agricultural production is to change unsustainable high-input management practices to low-input ones that can regenerate ecosystem functions: for example return ruminant livestock to open pastures and reduce whole-year stabling of animals (Teague 2018; see also section 3.6).

Non-crop structures such as green fallow areas, bushes, trees and open soil each provide specific niches for certain species. For example, the decline of fallow areas is a major driver of the decline of farmland birds at the European scale. Supporting the light management of fallow land within the new CAP eco-schemes can be a win–win strategy: it would simultaneously allow farmers to continue extensive weed control and enhance habitat quality for farmland birds (Tarjuelo *et al.* 2020; see also Pywell *et al*. 2015). Many species require different habitat types during a day, during a season or during their life cycle; hence it is often the combination of these elements that particularly fosters biodiversity and ecosystem services (Diacon-Bolli *et al.* 2012). The establishment and management of vegetated strips adjacent to farmed fields (including various field margins, buffer strips and hedgerows) are commonly advocated mitigation measures for negative environmental impacts of agriculture. Establishment of vegetation strips is one tool for improving the biodiversity and ecosystem services of the agroecosystems; however, the management of existing flower-rich landscape elements can provide similar good results. For example, von Königslöw *et al.* (2021) found that existing herbaceous habitat patches, such as hedges, field margins or ditches, can provide ample nectar sources for pollinators.

The European Landscape Convention aims to protect and sustain European landscapes characteristic of certain countries and cultures; and it considers the agricultural landscape not only as physical structures but

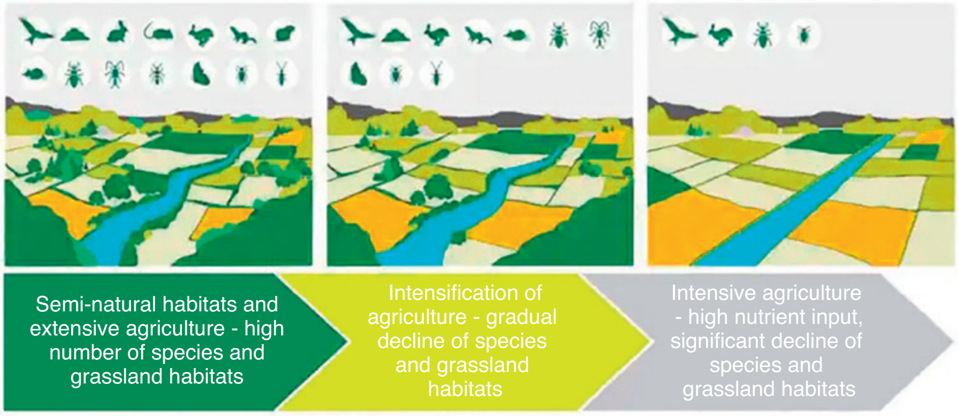

Figure 11 Decline in farmland biodiversity due to intensification of land use. Source: European Court of Auditors (2020).

also as cultural entities characterised by land-use types and cultural practices. There are some high-diversity landscape features that are included as characteristic landscape elements of certain countries (Jones *et al.* 2016); thus, their restoration and management should be considered a high priority.

4.3.2 Diversification of landscape configuration

Landscape heterogeneity provides an important source of resilience for agroecosystems. Agricultural landscapes that are composed of a small-grained and well-connected mosaic of early- and late-successional habitats may more likely harbour biota that contribute to regulating and supporting services for agriculture, compared with simple and cleared landscapes (Jackson *et al.* 2007) (Figure 11). More heterogeneous landscapes provide ecosystem services such as decreasing water and wind erosion, increasing protection against floods and extreme droughts, better filtering of surface and subsurface water, increasing populations of pollinators, reducing pest outbreaks, as well as resilient agricultural returns in uncertain market and climate conditions (Abson *et al.* 2013). When analysing the drivers of the recent dramatic decline of insects (67% of the biomass, 34% of the species within 10 years, 2008–2017 in German calcareous grasslands), Seibold *et al.* (2019) found that landscape-wide intensification and large proportions of arable land were the main drivers of the decline, rather than the intensification level at the local sites.

Temporal effects on yield can also be important: since landscapes dominated by arable land may have the highest average yields, semi-natural habitats may be more important in increasing yield stability and resistance to extreme weather events (Redhead *et al.* 2020).

Structural heterogeneity within and around grassland habitats, characteristic for historic landscape management, has vanished from large parts of Europe because of agricultural intensification, effective agricultural machinery or land consolidation (Diacon-Bolli *et al.* 2012). To increase the biodiversity of agroecosystems, it is crucial to restore landscape heterogeneity. One of the most evident ways to increase landscape heterogeneity is by decreasing the size of agricultural fields. There are several trade-offs related to field size: small fields are more costly to cultivate and edges can increase weed infestation; however, they can maintain higher biodiversity and can reduce the probability of pest outbreaks (Tscharntke *et al.* 2021). As an indicative size, fields smaller than 6 hectares are recommended for supporting biodiversity and ecosystem services. The optimal field size that supports the highest biodiversity and ecosystem services varies considerably across regions and crop types. In agroforestry, larger fields can be more favourable than small ones for supporting biodiversity and ecosystem services. In most arable cultures, however, larger field sizes result in coarse-grained landscapes, with lower diversity of crop types, field edges and non-crop habitats (Clough *et al.* 2020). Decreasing field size is a target that could be effectively monitored by easily measurable indicators based on remote sensing by satellite imagery.

On the basis of 435 landscapes across eight regions, Sirami *et al.* (2019) found that increasing configurational cropland heterogeneity by decreasing field size can be as beneficial for multitrophic diversity (plants, birds, bees, butterflies, carabid beetles, spiders and syrphid flies) as increasing the area of semi-natural habitats. This emphasises the importance of small field size for supporting biodiversity. However, decreasing field size might not be effective without increasing the proportion of semi-natural habitats in the surrounding landscape if the target is not only the number of species, but also species composition and the proportions of specialist, generalist and weed/pest species, which would require further analyses. In addition, to support agrobiodiversity, small field size should be complemented by sufficiently wide field margins that can provide shelter and food for several organisms. However, there can be a trade-off between biodiversity conservation and agricultural production as wide margins together with small field sizes can considerably reduce the area of the cultivated land.

Achieving a landscape-level mosaic of semi-natural habitat patches and fine-grained cropland diversification is key for promoting large-scale biodiversity in both conventional and organic agriculture (Tscharntke *et al.* 2021). It is important to critically evaluate whether organic farming or conventional farming with landscape diversification is more effective and cost-effective from the viewpoint of crop production and the maintenance of agrobiodiversity. This is important since the EU Biodiversity Strategy has the ambitious goal of cultivating 25% of all croplands under organic farming by 2030. In a recent critical review, Tscharntke *et al.* (2021) argued that allocating resources to the diversification and restoration of semi-natural habitats in conventionally farmed agricultural landscapes would be a better option for biodiversity than prioritising organic agriculture. This would especially be the case if the trend towards intensification within organic farming continues, because organic intensification diminishes the positive effects of organic management of the arable land, for example the longer, more complex and diverse crop rotations and longer periods with grass-legume leys (see, for example, Chongtham *et al.* 2017; Nkurunzisa *et al.* 2017). Batáry *et al.* (2015) showed in a meta-analysis that increasing landscape heterogeneity by off-field measures, such as field margins and hedgerows, are more than twice as effective in promoting biodiversity as in-field measures such as organic management. Compared with organic farming, higher landscape heterogeneity (Weibull *et al.* 2000) or higher edge length (Batáry *et al.* 2010) are approximately twice as effective in supporting the diversity of butterflies and birds, respectively. Hence a mosaic of non-productive (e.g. restoration) and productive de-intensified farming as well as field edge and semi-natural habitats would best support biodiversity and ecosystem services in landscapes dominated by arable lands (see, for example, Gayer *et al.* 2021).

4.3.3 Restoration in agricultural landscapes

The UN Decade on Ecosystem Restoration will give a new momentum to landscape-scale restoration efforts, but it is still important to use the limited resources for restoration in the most effective way. Tscharntke *et al.* (2021) argue that there is a threshold around 20% of semi-natural habitats in agricultural landscapes that is key to biodiversity maintenance. Below this threshold habitat loss causes disproportionally high losses in patch connectivity, which can disrupt exchange of organisms across the landscape, and threaten their survival probability. A recent perspective paper on global restoration targets also argues that 20% would be the minimum threshold of natural or (semi)-natural habitats in 'working landscapes' that can provide supporting and regulating ecosystem services (Garibaldi *et al.* 2021). Therefore, there is accumulating evidence that restoration efforts in agricultural landscapes should target at least 20% cover of semi-natural habitats to support multifunctional agricultural landscapes. This target can be the most easily reached and can have the highest impacts in more homogenous landscapes. The effectiveness of agri-environmental schemes at the field scale also depends on the landscape complexity, and is highest in more homogenous landscapes (Tscharntke *et al.* 2005; Batáry *et al.* 2015). In addition, besides the total area of semi-natural habitats in a landscape, their connection and spatial arrangement are also important, which can be enhanced by the restoration of ecological corridors, edge habitats and stepping stones.

When turning arable land into grasslands, the use of species-rich regional seed mixtures is recommended (Kiehl *et al.* 2010). The genotypes in such mixtures are best adapted to local site conditions, and the local origin of species ensures that strange genotypes are not introduced to the landscape. Addition of regional seed mixtures can also improve existing degraded grasslands in agricultural landscapes. More diverse grasslands decrease erosion, increase effectiveness of water purification and support diverse pollinators, thus providing better ecosystem services than arable land or short-lasting, species-poor intensive grasslands (Walden and Lindborg 2016; Squires *et al.* 2018; Bengtsson *et al.* 2019). Species-rich grasslands may also develop by spontaneous succession after abandonment of arable land if regular mowing is ensured (Lencová and Prach 2011).

The Biodiversity Strategy aims to have at least 10% of European farmland as high-diversity landscape features (fallow land, flower strips, hedgerows, field margins). Currently, approximately 4.1% of the utilised agricultural area in the EU is fallow land and 0.6% is covered by linear landscape elements (Barreiro-Hurlé *et al.* 2020). Therefore, to achieve the 10% target it is crucial to maintain the existing landscape features and to create new ones to approximately double the size of their total area. This type of landscape diversification could be the most effective where there is an existing green infrastructure containing semi-natural habitats, so the new features can be integrated into a functioning network of habitats. Seeds of most plant species have a chance for dispersal between patches that are at a maximum 100–150 metres from each other (Ozinga *et al.* 2004). For solitary bees, a tagging study investigating foraging distances found that flower strips should be maximum of 150 metres apart to ensure pollinator-mediated gene flow between patches (Hoffman *et al.* 2020). Increasing the extent of high-diversity landscape features and integrating them into the already existing green infrastructure are targets that can be effectively monitored by easily measurable indicators using remote sensing by satellite imagery.

However, note that there are cases where certain restoration measures can have contrasting effects at different spatial scales. For example, afforestation at the local scale can improve microclimate, carbon sequestration and soil water-holding capacity, and can reduce erosion. However, in arid and semi-arid regions where the natural vegetation consists of open habitats, large-scale afforestation campaigns can reduce the regional water table and can contribute to regional aridification (Tölgyesi *et al*. 2020). In such cases, landscape-scale restoration planning should be used and, instead of afforestation, restoration of species-rich hay meadows and extensive pastures is recommended to improve agricultural landscapes.

Woody habitats are important components of the European landscape and afforestation done in line with ecological principles can contribute to increased carbon capture and storage. The Biodiversity Strategy aims to plant at least 2 billion trees in the EU by 2030; however, it is important to concentrate this restoration effort into places where afforestation does not compromise already existing biodiverse habitats (see above).

4.3.4 Landscape-scale management

There is limited knowledge about the most suitable scenarios for improving landscape-scale heterogeneity. Harlio *et al.* (2019) demonstrate how to obtain conservation prioritisation solutions that would simultaneously address three goals: minimising local habitat quality loss, maximising habitat connectivity and incorporating landscape heterogeneity by using a zonation prioritisation tool. Synergies between landscape-scale factors suggest a high potential for reconstruction of a functioning network of semi-natural grasslands in areas under intensive agricultural use. To successfully apply multiple diversification measures at the landscape level it is essential that stakeholders work together, because achieving optimal results may require systems redesign at the landscape scale (Kremen and Merenlender 2018; Kremen 2020; Pretty *et al*. 2018). For example, the use of landraces can be upscaled to larger spatial scales by promoting seed exchange networks within farming communities. Seed exchange networks can support social organisation, knowledge transfer and the sustainability of rural economies (Pautasso *et al.* 2013). Better coordination of management practices at the regional level could thus upscale the field- or farm-scale benefits of agri-environmental schemes to the landscape scale. To increase the efficiency of such regional initiatives, the targeted marketing of agri-environmental schemes to farmers with potentially high-quality sites, or higher compensation to maintain higher-quality sites, could be effective measures. Another important step is to establish subsidy systems not only for individual farmers, but also for groups of farmers within the framework of National Rural Development Programmes. These schemes support coordinated actions at multiple farms within the landscape to achieve more positive effects at the landscape scale (Prager 2015).

4.3.5 Localisation

Regenerative agriculture should be based on localisation: land should be used for products that can be cultivated in the long-term without sacrificing regulating and supporting ecosystem services, with the aim of shortening the production and consumption chains, bringing products closer to the customer. Localisation is a bottom-up process and the currently existing top-down regulations and structural policies do not support localisation; instead they are supporting centralisation and homogenisation. Transitioning to a regenerative agriculture should also involve subjective, non-material factors operating at individual, household and community scales that are associated with culture, values, ethics, identity and emotion, and that interact with regional, national and global processes (Gosnell *et al.* 2019). Regenerative agriculture should be fitted to the local conditions and based on locally available resources and nature-based solutions. Localisation implies adapting those available practices that suit the local conditions (climate, soil, land cover types, socio-economic environment) the best. Hence, localisation means producing a variety of products locally in low-input systems in the local environmental and socio-economic context. Of course, a complete local production is neither desirable nor achievable. For instance, an approximately 100-kilometre radius foodshed can sustain approximately the 70% of commodities needed for local residents in and around a medium-sized city (the example of Avignon: Vicente-Vicente *et al.* (2021)).

Another important aspect of localisation is the flexible application of those farming practices that fit the local environmental and socio-economic context the best. Local farmers should have some flexibility and decision to choose and implement those practices that are the best local solutions (see also Diacon-Bolli *et al.* 2012). This can be achieved by result-based subsidies and adaptive management: as long as the biodiversity targets are achieved, farmers can select the locally most suitable management practices (Herzon *et al.* 2018). It is important to note that, given the large differences in geographical, biological, social and cultural diversity between regions, certain practices can be beneficial in one location but less suited to others (e.g. Báldi and Batáry 2011; Tryjanowski *et al.* 2011). In arid or semi-arid regions, intensive irrigation and extensive tree planting should be avoided as these can accelerate the aridification processes at the landscape scale. In such regions, extensive livestock grazing can be a more sustainable land use.

4.4 European agriculture and the role of animals

Regenerative agriculture practices explicitly include the role of farm animals both in carbon management and biodiversity. The effect of farm animals on carbon balance is context-dependent and largely depends on the type of animal husbandry considered. Methane emissions from ruminants can be decreased to some extent by improving the nutritional status of animals, the quality of the forage base, and supplementation of known methane-mitigating compounds (Thompson and Rowntree 2020). Other negative effects on carbon balance can be counterbalanced to some extent when livestock farming contributes to the maintenance of permanent pastures and meadows, and extensive grazing results in these systems becoming net sinks for GHGs (Bellarby *et al.* 2013; Koncz *et al*. 2017).

There are several approaches to decrease the negative environmental impacts of livestock, not only in low-input systems but also in high-input systems by introducing spatial and temporal heterogeneity into farming practices. Rotational grazing regimes can have fewer negative impacts on soils and vegetation compared with continuous grazing (di Virgilio *et al.* 2019). Using crop rotations or cover cropping can also be a tool for improving the provision of ecosystem services, even in high-input livestock farms.

In low-input grazing systems, of special interest is so-called High Nature Value (HNV) livestock farming which uses few external inputs and relies predominantly on semi-natural forage. These systems are found mainly in marginal, sparsely populated rural areas where physical factors, and in some cases social factors, have prevented intensification of land-use (Beaufoy 2017). HNV farming is a viable solution for providing the co-benefits of biodiversity conservation and agriculture. This farming type can be considered as best practice of regenerative agriculture: in this case, agriculture drives conservation of biodiversity and ecosystem services (Bengtsson *et al.* 2019). Besides that, HNV farming can be a major source of income in rural populations and can contribute to rural development through the utilisation of otherwise marginal and unproductive land. Many elements of HNV farming are integral parts of cultural heritage and traditional ecological knowledge (Molnár and Babai 2021). Extensive grazing systems also provide higher-quality products than farming systems based on stabled animals: for example, dairy products from extensively grazing livestock had much higher quality in terms of higher levels of unsaturated fatty acids, vitamins and phenols (Cabbidu *et al*. 2019) than those from stabled animals.

For regenerative extensive pastoral grazing systems, the most suitable livestock type that can best utilise and manage the habitats under consideration should be chosen. For instance, for managing shrub-encroached semi-natural grasslands, goat pasturing can be a feasible solution (Elias and Tischew 2016). Robust, endemic local breeds can be the most effective for the management of environmentally harsh habitats; however, studies comparing the effects of different breeds of the same species are scarce (but see, for example, Kovácsné Koncz *et al.* 2020; Pauler *et al.* 2019). Knowledgeable herders who have a deep traditional and local knowledge of sustainable grazing practices can help to use the pastures in a way that is best for both biodiversity and animal welfare. Increasing the reputation of a profession called 'conservation herder' (Molnár *et al.* 2020) through training and supporting policies could be a major step towards managing extensive pastures according to the principles of regenerative agriculture.

Besides farm animals, wild game species are also an integral part of the European agricultural landscape that provide important ecosystem services and disservices (Pascual-Rico *et al.* 2021). They are important consumers and seed dispersers and they create establishment microsites for plant species. However, overabundant game populations, especially wild boars, often provide ecosystem disservices by being crop pests and disease vectors, and by causing degradation of the natural grassland and forest habitats. Maintaining wild game populations at an optimal level can be a good strategy to mitigate ecosystem disservices and to harvest high-quality and nutritious meat from agroecosystems.

4.5 European agriculture and climate adaptation

A major difficulty in anticipating strategies for regenerative agriculture is that there are many uncertainties about the local effects of climate change. Rather than a simple rise in temperature or CO_2 concentration with predictable variation, increasing global temperatures will result in more unpredictable weather, with more and more extreme events such as longer droughts and more intense rainfall. In this context it will be a significant challenge to identify universally applicable conventional technological improvements that can beimplemented incrementally, such as breeding crops for early-season drought or mid-season waterlogging, if erratic conditions could lead to early-season waterlogging and mid-season drought. In addition, one stressor rarely comes alone: heat stress is often accompanied by drought stress or high ultraviolet irradiation. The ability of plants to cope also depends on the temporal aspects of stress. An additional challenge lies in our still poor understanding of plant responses to different environmental conditions. Scientific knowledge is limited for most crop species, and fragmentary for landraces selected for local climatic conditions. There is a lack of mechanistic understanding of how temperature is perceived by plants, their recovery processes, and the mechanisms by which memories of environmental changes are genetically encoded (lifetime and transgenerational epigenetic stress memory). For each plant, there is a range of temperatures and environmental conditions to which it can adapt to survive, with some physiological plasticity, but it is not very well determined for each crop species.

This is why climate adaptation must be built on system-level transitions towards resilience (see examples in Box 3). In particular, there is a win–win situation in mitigative restoration of carbon stocks (Paustian *et al.* 2019) in soil by carbon farming (COWI, Ecologic Institute and IEEP 2021). These practices simultaneously and adaptively build and maintain soil fertility, water holding and infiltration, nutrient holding, cation exchange capacity, and structural resistance to compaction and erosion. Rotational (temporal) diversification at parcel or field levels almost inevitably brings spatial diversity of crops within and between farms, provided that crop sequences are spatially asynchronous over time. Mixed farming with grazing livestock (ruminants) at sustainable stock sizes is a natural way to maintain within-farm and regional diversity for resilience. Adaptive functional diversity can also be increased by cultivar mixtures or by within- and between-farm diversity of cultivars with variable traits to meet climate variability (Mäkinen *et al*. 2016). Together, increasing diversity, reducing food-chain connectivity and increasing decision-making autonomy increase resilience and adaptive capacity of the food system to meet the challenges posed by climate change (Rotz and Fraser 2015).

Most of the adaptation measures mentioned in Box 3 address concepts and approaches similar to those included under the umbrella of regenerative agriculture; they are often included in various adaptation assessment frameworks, including adaptation planning and operation by stakeholders, farmers, policy-makers and scientists (Visinho *et al*. 2021).

4.6 European agriculture and the role of innovation and novel technology

Europe has great potential for reaching ambitious goals in the agricultural sector. For example, regenerative

Box 3 Examples of climate adaptation measures

A. Water management

1. Water saving in irrigated agriculture

Elimination of water transport losses
High-efficiency irrigation systems
Accurate calculation of irrigation doses
Adoption of deficit irrigation methods
Use of recycled water or water from desalinisation plants
Use of crops and cultivars with shorter biological cycles

2. Water management in dryland agriculture

Increase soil water storage capacity (appropriate cultivation techniques, addition of organic amendments)
Water harvesting and storage in reservoirs during the rainy period
Insulating storage reservoirs to reduce seepage to ground water
Use of crops and cultivars with shorter biological cycles and drought resistance

3. Water management in wet climates

Drainage
Inlet systems for surface runoff
Flood control measures
Wetland restoration

B. Modification of crop genetic resources

Breeding of new cultivars more resilient under changing climatic conditions
Understanding crop/weed interactions under changing conditions

C. Modification of crop management

Shifting crop cultivation zones to northern latitudes and high altitudes
Modifying crop management techniques (timing of planting, plant protection, fertiliser applications, harvesting, etc.)

agricultural methods, which aim to restore ecosystems, to increase the capacity of the landscape to capture and store carbon, and to maintain biodiversity, could be combined with modern plant and animal breeding and with implementation of new technologies. Such technologies could include, for example, remote sensing based on satellite technology, precision farming and modern sensors, crop surveillance using drones and virtual fencing[5].

Technological innovation and modern breeding methods could, in combination with regenerative practices, significantly improve management of plant growth and soil fertility while also contributing to disease control, for example, and to reducing the need for pesticides and fertilisers.

Plant breeding traditionally uses natural biodiversity and usually takes many years (5–10 for most European crops, or many more in the case of fruit trees). The major problem in plant breeding is to identify the traits of interest and the corresponding genes. In addition, most of the traits of interest are complex, have a multigenic basis and often interact with each other. Although the tremendous progress in gene sequencing during the past 20 years has now resulted in complete genomes for most crops and functional characterisation of a large number of genes, knowledge is still incomplete and largely limited to laboratory rather than field situations, and to a few model species (EASAC 2017b). Resequencing genomes of multiple varieties of the same species has revealed an impressive genetic diversity, with presence or absence of some genes, changes in copy numbers, multiple alleles, variations in repeated sequences and transposable elements. This genetic diversity is probably the basis for plasticity and adaptability specific to different crops. Although this genetic diversity is described and available for most crops, it remains to be exploited and correlated with plant behaviour in a given niche. Most of the time, the most favourable combinations of alleles for a given situation remains to be identified. Genome-wide association mapping should help identify important genes for adaptation to climate change and improve development of new varieties. However, the uncertainty about future climate and weather conditions makes the relevance of such mapping difficult to predict, highlighting the need for developing resilient varieties that are robust when facing novel climates and environmental conditions.

Traditional breeding makes use of this information, but is a complex, expensive and time- and land-consuming process. Gene editing technology has evolved rapidly and the CRISPR–Cas9 system and its derivatives now allow introduction of a new gene or modification of an allele in a genome with high precision, without leaving any trace of the transformation. In many cases, it is impossible to distinguish the new gene or the new allele from its counterpart in nature. EU regulation targets the technique used to introduce the new gene or new allele rather than the trait itself, or the consequences of the trait. Given the rapid advances in techniques such as gene editing, and their potential benefits, EU regulations on new breeding technologies need to be revisited, through a discussion that is based on the traits of the plant in a systems perspective, rather than on the technology (EASAC 2017b). Any new regulations should be evidence-based, and clearly apply the precautionary principle when balancing benefit–risk ratios. Even if this is successful, it is important to stress that we cannot rely only on genetics and breeding to meet all future challenges: we have always to combine these approaches with good agricultural practices, such as rotation of culture and diversifying varieties and landscapes. Furthermore, focusing on biotechnology as a technical paradigm may result in lock-ins that impede the development of agroecological innovations, despite the fact that such innovations are probably the key to sustainable agriculture and addressing climate change (Vanloqueren and Baret 2009).

Given the climate and biodiversity challenges, innovation needs to happen not only in technology and practices, but also in social and institutional contexts. This is also emphasised by the skewed demography among European farmers, with an average of more than 55% older than 55 years: for example 73% in Portugal, 70% in Bulgaria and 68% in Italy (Rovný 2016). Several initiatives have been taken around Europe to attract a young generation of farmers, including schemes for shared ownership, contract farming, micro-farming and indoor farming in peri-urban and urban areas. There is a need for an EU-wide strategy to support such social and institutional innovations in agriculture as well as training and education, and to enable financial and legal conditions for up- and out-scaling of promising and attractive new forms of farming.

4.7 European agriculture and the Common Agricultural Policy

The Common Agricultural Policy's (CAP's) main aim is to regulate land governance in agriculture and to present landowners with incentives for better practices that preserve and protect both humans and habitats. Previous CAP policies have often been a strong driving force for intensification of farms, especially in countries that have recently joined the EU. The CAP's first pillar and its direct payments have been an incentive for EU

[5] Virtual fencing technology is operated via GPS technology and restricts animal movement without physical boundaries through auditory and electric signals that are communicated by neckband devices.

agriculture to produce fewer crops on excessively large fields, which have reduced biodiversity and increased homogenisation of landscapes, sometimes also resulting in overuse of land resources. The new CAP policies are more in line with what we have described here as regenerative agricultural practices, in particular the EU's soil protection policies, as set out in the current soil thematic strategy[6].

Sustainable soil management is viewed as essential for many strategies and priorities of the European Green Deal, including the Farm to Fork Strategy; the Biodiversity Strategy; the ambitions for climate change mitigation and adaptation; the Carbon Farming Strategy; and the new EU Soil Strategy for 2021. However, there are indications that soil erosion continues to outstrip soil formation across the EU, although the CAP is narrowing the gap (Panagos *et al.* 2015). In the latest EU Farm Structure Survey (2016), data on soil conservation measures (i.e. reduced tillage, cover crops and plant residues) were used to estimate the changes of the cover-management factor in Europe between 2010 and 2016. Among the different soil erosion risk factors, the cover-management factor has proved to be a suitable indicator that policy-makers and farmers can most readily use to help reduce soil loss rates.

Another aspect of regenerative agriculture and soil health is nitrogen supply to the soil through cultivation of legumes (EU Commission Report 2018). Nitrogen fixation provides available and 'free' nitrogen in the soil for the next cultivated species grown in the same field. The cultivation of legumes is an important link in regenerative practices and can significantly contribute to reducing fertiliser use. Also, legume-based grassland–livestock systems have multiple benefits such as reduced dependence on fossil energy and industrial nitrogen fertilisers, lower quantities of harmful emissions (GHG and nitrate), lower production costs, higher productivity and increased protein self-sufficiency (Lüscher *et al.* 2014). The CAP provides several instruments that directly or indirectly support or acknowledge the environmental benefits of leguminous crops. Under the new CAP 2021–2027 programme and budgetary framework, the development of protein crop production is an important component in achieving many of the CAP's objectives, and the Commission envisages advice and support on how to include plant proteins in national strategic plans to support member states in defining targeted measures.

Within the CAP at the farm scale, at least 3% of arable land will be dedicated to biodiversity and non-productive elements, with a possibility to receive support through eco-schemes to achieve 7%. In addition, wetlands will also be protected. Currently, there are no clear mechanisms at the landscape scale, but it may be possible to initiate policies for small farms to form cooperatives for biodiversity and thus potentially address the greater landscape scale that is important for biodiversity.

Under the CAP, the link between the receipt of income support payments and the production of specific products has been progressively removed ('decoupled'). This is to avoid overproduction of certain products and make sure that farmers are responding to genuine market demand. However, in some situations targeted aid to a specific agricultural sector or sub-sector may be needed if it is undergoing difficulties. Therefore, EU countries may continue to link (couple) a limited amount of income support payments to certain sectors or products. This is subject to various conditions and to strict limits to mitigate the risk of market distortions. To what extent the new CAP will be instrumental in the implementation of the Farm to Fork and Biodiversity Strategies is too early to judge, but there are important CAP elements (such as those mentioned above on soil protection, restoration and biodiversity) that, if widely implemented, should have a significant effect on the sustainability of European agriculture.

4.8 European agriculture and the multifunctional landscape

Regenerative agriculture is a concept that targets the coexistence of agricultural productivity and biodiversity. This dual aim can be best achieved in multifunctional agricultural landscapes (Frei *et al.* 2020). Sustainable multifunctional landscapes are 'landscapes created and managed to integrate human production and landscape use into the ecological fabric of a landscape maintaining critical ecosystem function, service flows and biodiversity retention' (O'Farrell and Anderson 2010). There is a trade-off between the provisioning services and other ecosystem services in agricultural landscapes: with increasing amounts of non-crop habitats, supporting, regulating and cultural ecosystem services increase while provisioning services decrease (Landis 2017; and see Figure 12). Ecological studies can provide guidelines for planning the configuration and composition of non-crop habitats at the landscape scale to maximise the biodiversity and ecosystem services (see section 4.3.2). Even in highly simplified landscapes, to maintain provisioning services in the long term, it is inevitable to protect and maintain supporting services by restoring high-diversity landscape features or semi-natural habitats (see section 4.3.3).

It is important to mention that agricultural landscapes should be multifunctional also because the large human

[6] https://ec.europa.eu/environment/soil/three_en.htm

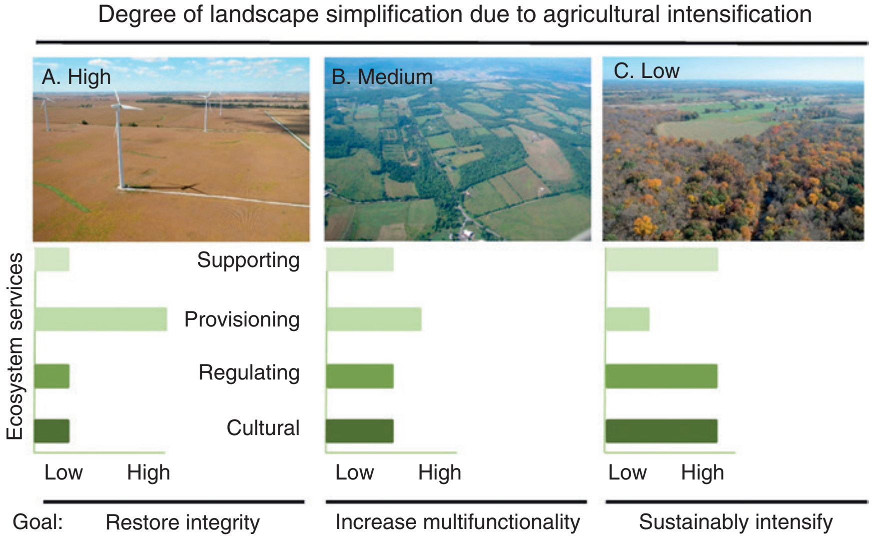

Figure 12 Relative levels of ecosystem services provided by agricultural landscapes along a gradient from highly simplified to complex landscapes. Source: Landis 2017.

population cannot be 'fed' from the entirely extensive agricultural approaches; thus some intensification is inevitable. However, how such intensification is made, often framed as sustainable or ecological intensification (Godfray *et al.* 2010; Garnett *et al.* 2013; Bommarco *et al.* 2013), and which and where innovative technologies need to be applied, matters (see also discussion around land-sharing and land-sparing in Sidemo-Holm *et al.* (2021)). This will most likely vary substantially according to regional social and environmental circumstances. Along with the huge effort and investment needed for restoration and regeneration in the near future, it is absolutely crucial to keep traditional and sustainable farming systems and the related traditional ecological knowledge, which still exist in remote and economically underdeveloped regions mainly in eastern and southern Europe. They are not only often agricultural-biodiversity hotspots but also important teaching and training areas for understanding coevolution of humans and nature, including multiple aspects that cannot be studied elsewhere.

4.9 Implementation of the Farm to Fork Strategy outside the EU

The EU is the world's biggest exporter and third largest importer of agri-food products and seafood (EU Commission 2021); it is thus a major player in a vast global trade network. Given this significant trade, the EU has to start focusing on the regulatory reforms required to ensure that all agricultural products that enter the EU market do not contribute to massive deforestation, loss of biodiversity, and GHG emissions in other regions (e.g. unsustainable production of cereals and field crops, soy, cattle feed and meat), or to net plant nutrient imports to the EU in feed and food products while resulting in net nutrient exports, soil mining and loss of soil fertility in the countries of export.

Although the potential of agricultural landscapes in Europe to increase carbon capture and storage in the next few decades is large (see previous sections), most GHG emissions from agricultural products in the EU derive from products exported to, and consumed in, the EU, with the corresponding GHG released in non-EU countries, such as in Latin America, India and Africa. Agriculture, land use and forestry practices (particularly deforestation is a large source of GHG emissions) in these regions are not managed with the same regulatory standards as in Europe, yet European manufacturers and consumers indirectly support the maintenance of these practices as global value chains are highly integrated.

The Farm to Fork Strategy points out that Europe cannot make a change unless the rest of the world is in some form of alignment, since obviously the EU itself may often contribute to negative environmental and social impacts in the countries where the traded commodities are produced. Therefore, efforts to tighten sustainability requirements in the EU food system should be accompanied by policies that help raise standards globally, to avoid export of unsustainable practices. The Strategy proposes to conduct this through EU external policies, including international cooperation and trade policy. However, the increased standards in the EU are already causing trade tensions with third countries. The EU needs to facilitate a broader movement, beyond current World Trade Organisation standards and obligations, to take on board third countries and allow them appropriate access to the EU market. In the post-COVID-19 world, actions may also include further exploring the potential climate and environmental effects of current trends of more local and regional sourcing of food, and the multiple consequences of decreasing long-distance supply chains in the global food trade.

5 Policy recommendations

Our evaluation of the concept of regenerative agriculture has revealed clear advantages when it comes to developing policies for sustainable agriculture. Regenerative agriculture is not viewed as defined *a priori* by a given set of rules and practices; instead, the goals that should be achieved are set and then practices and new technologies are adopted over time which contribute to achieving these goals. Hence the concept is viewed as broader and less prescriptive than other related concepts and does not exclude the use of, for example, modern plant and animal breeding technology, tilling, and use of inorganic fertilisers or pesticides.

There is therefore a high flexibility when it comes to searching for synergies between the goals of maintaining agricultural productivity, increasing carbon capture and storage, and enhancing biodiversity. However, the main limitation with regenerative agriculture in our view is that, as yet, only the field and farm scales are addressed. Our analysis of a large body of literature reveals the importance of landscape-scale perspectives and interventions (restoration) for maintaining biodiversity and ecosystem services. On the basis of these results, we argue that the concept would be even more useful if landscape- and larger-scale processes are explicitly addressed (see Figure 13 for a summary).

Below we propose policy recommendations, based on the analyses made in this report and our review of the literature, that will contribute to the main targets in the Farm to Fork and Biodiversity Strategies and be relevant for member states' implementation of the new CAP and development of policies for carbon farming in the EU.

The Farm to Fork and Biodiversity Strategies targets

- Agriculture to contribute to a reduction of at least 55% in net GHG emissions by 2030.
- Reduction by 50% of the use and risk of chemical pesticides and the use of more hazardous pesticides by 50% by 2030.
- A reduction of nutrient losses by at least 50% while ensuring that there is no deterioration in soil fertility, reduction of the use of fertilisers by at least 20% by 2030.
- Reaching 25% of agricultural land under organic farming by 2030[7].
- A minimum 10% area under high-diversity landscape features.

A General policy recommendations

Successful implementation of the Farm to Fork and Biodiversity Strategies depends on the following:

- Policy development and implementation made in a global food system context.
- Addressing a shift from a dominant focus on the volume of food produced to the nutritional and environmental quality of food; this requires a holistic food system approach.
- Always considering potential impacts in the production chain of changes in the consumption chain, such as dietary shifts and reduction of food waste.
- Emphasising the multifunctional dimensions of agricultural landscapes, including ecosystem services, recreation, tourism, and human health, particularly close to urban centres.
- Providing predictable and long-term agri-environmental support to farmers to enable a sustainable shift to regenerative agriculture.
- Flexible long-term support for sustainable innovative and local transformative change initiatives, such as adopting new regenerative practices, new or modified crops and machinery, innovative business models, agri-business start-ups, institutional systems for coordination at landscape-scale, innovative urban–rural linkages, etc.
- Substantial increase in EU and national investments in localised education, training and extension services.
- Avoiding exporting negative environmental externalities to countries outside the EU.

B Policy recommendations at the farm scale

EASAC recommends placing special emphasis on support for the following practices, which show synergies between carbon capture and storage, particularly in soils, and enhancing biodiversity, while having no or limited negative effects on food production:

- Increased diversification within and among crops.
- Introduction of permanent and perennial crops.
- Expanded agroforestry and intercropping.
- Strive for green plant cover on all farm fields during all seasons, reduce tilling.

[7] A critical analysis is necessary to make sure that this target really supports biodiversity and ecosystem services. Is it possible to produce enough food if 25% of agricultural land is managed under organic farming without increasing the area of cultivated land or without substantially intensifying organic farming practices? There are several harmful intensification practices in organic farming that should be minimised or avoided (Tscharntke *et al.* 2021).

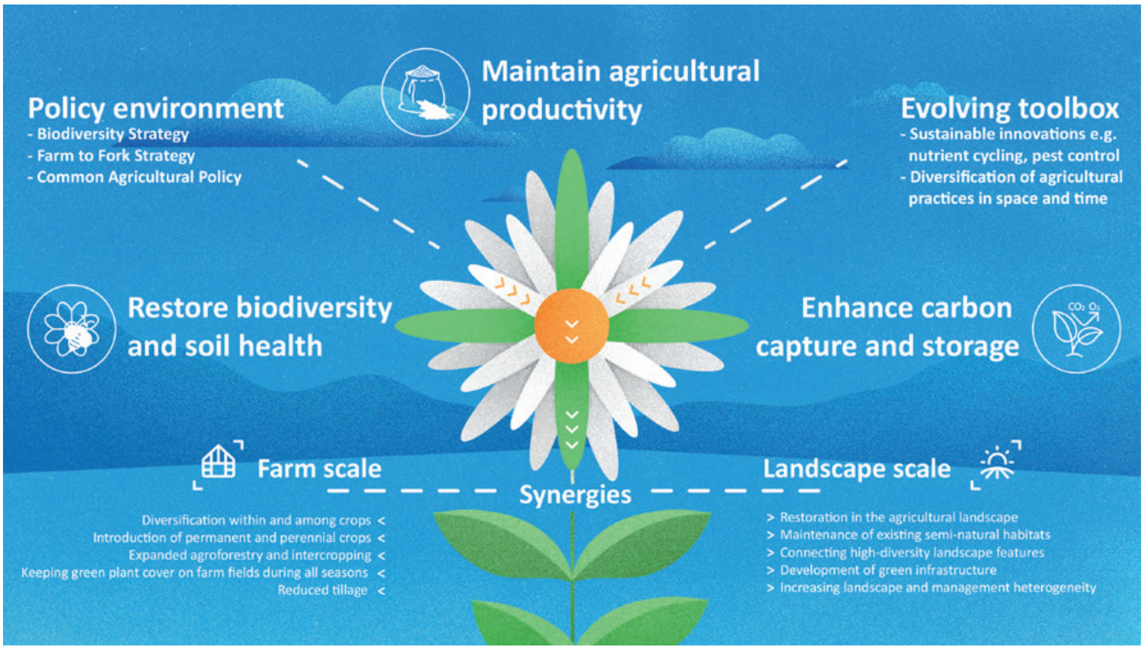

Figure 13 Summary: three pillars of regenerative agriculture, its policy and technology/practice context and the synergies at farm and landscape scale evaluated in this report.

- Targeted support systems and information campaigns about CAP eco-schemes to farmers managing sites with higher natural values.
- CAP eco-schemes should also target smallholder farms since smaller field sizes in general support higher biodiversity and ecosystem service.

C Policy recommendations for the landscape scale

- Develop schemes that support better coordination of management practices that simultaneously enhance biodiversity and carbon capture and reduce net GHG emissions at the landscape/regional scales.
- Stimulate schemes that benefit not only individual farmers but also communities and groups of farmers, for example within the framework of National Rural Development Programmes.
- Promote sustainable innovations for rural–urban–rural cycles of nutrients.
- Adapt and develop meaningful indicators that can be easily measurable over large spatial scales, such as field size or the extent of high-diversity landscape features.

Policy recommendations for restoration in the agricultural landscape

- Prioritise restoration in agricultural landscapes where there is an existing green infrastructure containing semi-natural habitat patches.
- Besides creation of new high-diversity landscape features, prioritise conservation and management of existing ones.
- Support restoration measures that increase landscape complexity.

Policy recommendations for localisation

- Land should be used for products that can be cultivated in the long-term without sacrificing regulating and supporting ecosystem services, often with the aim of shortening the production-consumption chain.
- More flexibility should be given to farmers in their management decisions. This could be achieved by employing the concept of adaptive management: as long as the targets (food production, carbon storage, biodiversity, ecosystem services) are maintained, farmers should have flexibility in choosing and varying the management options from a toolkit that suits the local conditions.

Policy recommendations for animal husbandry

- A shift from intensive year-round stabling animal husbandry towards extensive pastoral systems should be supported by CAP eco-schemes. Grazing and mowing in High Nature Value grasslands should be recognised as best practice for maintaining biodiversity and ecosystem services and providing high-quality meat products.

D Policy recommendations for tree planting in the agricultural landscape

- Mixtures of tree species planted in agricultural landscapes should be carefully selected with regard to their traits and genetics to be able to survive under different climate scenarios and generate valuable ecosystem services.
- Such trees should become more common in many intensified agricultural landscapes in regions with a historical presence of trees in the landscape.
- Prioritise and support trees as high-diversity landscape features in arable landscapes and in agroforestry.
- Increase the number of trees in urban and peri-urban areas, since these may also contribute to improve local climate and livelihoods; public outreach and environmental education.
- Avoid tree planting in regions where open habitats constitute the native vegetation, such as in (semi-) arid regions.

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Appendix 1 Working Group composition, acknowledgements and peer reviewers

The report is a result of multiple discussions in the EASAC Environmental Steering Panel, the Biosciences Panel, EASAC Bureau and the Council of EASAC during 2020 and 2021. The project proposal was approved by EASAC Council in November 2020, and EASAC's member academies nominated experts to form a Working Group in the first quarter of 2021. An international Working Group of European experts jointly developed the report during 2021.

The first meeting was held on 30 March 2021, chaired by Lars Walloe, EASAC and Orsolya Valkó from the Hungarian Academy of Sciences. At this meeting we were very grateful for the participation of Mike Mackenzie from DG AGRI, EU Commission, who outlined the future development of the Common Agricultural Policy and the Farm to Fork Strategy. We also appreciated the contribution by Anna Seip from the Research and Innovation Unit, DG AGRI, who outlined the future Horizon Europe investments in agricultural-related issues.

The project has benefited from several ongoing and previous projects of EASAC which are relevant for this report. Of particular relevance is the report **Sustainability and health of Europe's soils**, which examines the threats to the sustainability of soil productivity, the potential contribution of soils to worsening or mitigating climate change, the importance of soil biodiversity, and interactions between soil health and human health. EASAC's previous project **Multi-functionality and sustainability in the European Union's forests** is also highly relevant. The EASAC Biosciences Programme has also produced several reports relevant to this study, such as **The imperative of climate action to protect human health in Europe** (which addresses agriculture), **Global food security**, and the EASAC Commentary and Statement on new breeding techniques in agriculture (which includes issues for climate-resilient agriculture).

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All Working Group meetings were held virtually in 2021 because of the COVID-19 pandemic. Working Group meetings were held on 25, 26 and 30 March; 30 June; 1 July; 13 and 14 September; 14 and 15 October. The report was based on the scoping paper approved by EASAC's Council and developed by incorporating feedback on several draft versions discussed during Working Group meetings and shared by e-mail.

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Appendix 2 Methods for analysing the evidence base about regenerative agriculture practices

For each practice included, we searched for meta-analyses and systematic reviews examining the effect of the practice on carbon capture or storage, biodiversity, using search terms ‘meta-analysis systematic review (practice name) carbon capture storage / biodiversity / GHG emission’ where ‘/’ indicates the effect in each respective search. We categorised the different practices of agricultural diversification into three major groups: within-crop, between-crops and landscape-scale diversification. We performed this literature search in the ISI Web of Knowledge and Google Scholar search platforms, and screened the journals *Conservation Evidence* and *Environmental Evidence*. We prioritised searches for systematic reviews and meta-analyses, but also included original research articles where relevant. This means that we have not performed a full search for all evidence about each practice, as this would have been very time-consuming. In some cases, we made use of our specific knowledge of certain practices to find relevant research in the absence of meta-analyses, although this was not done systematically.

Appendix 3a Evidence about the effects of different regenerative agriculture practices on carbon capture and storage (and soil organic matter)

Practice	Support for increased carbon capture and storage/soil organic matter	Type of evidence	Remarks	Key references
Conversion of arable land to grassland	Positive	Field studies, reviews (a), meta-analysis (b)	Good evidence that conserving permanent grasslands is positive for carbon storage (e.g. Li *et al.* 2020) (See also Figure 9 which shows data from Smith 2014 and Kämpf *et al.* 2016).	(a) Freibauer *et al.* 2004 (b) Kämpf *et al.* 2016
Agroforestry	Positive (*ca.* 17%)	Analysis of previous meta-analyses (global) (c)	Across all agroforestry types. Evidence from Europe less conclusive, but practice has substantial potential (Aertsens *et al.* 2013; Kay *et al.* 2019). Generally highest effects in tropical, subtropical and Mediterranean areas (Thomas Kätterer, personal communication).	(c) Beillouin *et al.* 2021
Wetland/peatland conservation or restoration	Positive (but variable)	(a) review	Depends on landscape configuration (Villa and Bernal 2018).	(a) Lamers *et al.* 2015
Woodland (wood pastures; silvopasture)	Inconclusive	Insignificant but negative effect on soil quality in meta-analyses (c; only few studies)	Unclear controls (from information in (c)). Needs more study. Reference (c) provides results on soil quality indicators, not specifically carbon capture or soil carbon storage, but usually soil carbon seems similar to overall effects (c, suppl. materials).	(c) Beillouin *et al.* 2021
Hedgerows, woody buffer strips, farmland trees	Positive (*ca.* 11%)	Analysis of previous meta-analyses (global) (c)	Reference (c) provides results on soil quality indicators, not specifically carbon capture or soil carbon (see above). Hedgerows have been shown to increase soil carbon relative to other edge habitats (Mayer *et al.* 2022; Van den Berge *et al.* 2021; see below).	(c) Beillouin *et al.* 2021
Increased diversity in crop rotation	Positive (*ca.* 5%)	Analysis of previous meta-analyses (global) (c)	Reference (c) provides results on soil quality indicators, not specifically carbon storage or soil carbon (see above). For future studies it is important which crop rotations are used (e.g. if they include semi-permanent crops) (cf. King and Blesh 2018).	(c) Beillouin *et al.* 2021

Practice	Support for increased carbon capture and storage/soil organic matter	Type of evidence	Remarks	Key references
Crop diversity as cover crops	Positive (*ca.* 8%)	Analysis of previous meta-analyses (global) (c)	Impact largely dependent on whether or not legumes are present in the cover crop mixture (c). In a global scenario estimated potential carbon sequestration of 0.12 petagrams of carbon per year with saturation after 155 years (Poeplau and Don 2015) (see above).	(c) Beillouin *et al.* 2021; Poeplau and Don 2015; Shakelford *et al.* 2019
Crop diversity as intercropping	Positive: (*ca.* 10%)	Analysis of previous meta-analyses (global) (c)	(Variety mixtures had no positive effects on soil quality indices (a; cf. King and Blesh 2018) see above).	(c) Beillouin *et al.* 2021
Minimised tillage: reduced, minimum or no tillage	Increase in carbon <30 cm soil depth; no effect on total soil carbon	Meta-analysis	Variable results reported in (d), but results support increase in upper soil layers but small effect (if any) on total soil carbon (d) (Meurer *et al.* 2018). Bai *et al.* 2019 report 5–10% increase depending on tillage intensity.	(d) Haddaway *et al.* 2017; Bai *et al.* 2019
Retaining crop residues in field or on soil surface	Positive (*ca.* 6%)	Meta-analysis	Bai *et al.* (2019) report positive usually but varies between irrigated (+) and rainfed (not significant) and with soil type	Bai *et al.* 2019
Perennial crops	Positive (*ca.* 12%)	Meta-analysis	Comparison of crop rotations with/ without perennial crops (d).	(d) King and Blesh 2018
Biochar	Positive (30–40% often reported)	Meta-analyses of various systems	Note: no *Environmental Evidence* reviews. Several studies from China. Also viticulture.	Liu *et al.* 2016; Bai *et al.* 2019; Xu *et al.* 2021. Also Payen *et al.* 2021.
Avoid pesticides (a consequence of other practices; see below)	No data	—	Few studies explicitly examining whether pesticide applications had effects on soil. Sometimes negative, if pesticides affect soil microorganism activity: Nathan *et al.* (2020).	—
Field borders, etc. for beneficial insects (pollinators, etc.)	Inconclusive	Field study	Based on Falloon *et al.* (2014), the potential for larger carbon storage by flower strips is small, while hedgerows have larger potential. Few data exist. Grass strips were not increasing soil carbon, while hedgerows were in a Belgian study with low *n*-values (*n*=6) (see above).	Van den Berge *et al.* 2021.

Appendix 3b Evidence about the effects of selected regenerative agriculture practices on various aspects of biodiversity (farm scale)

See also Appendix 4 for more detailed examination of diversification measures.

Practice	Effect on biodiversity (general or specific)	Type of evidence	Remarks	Key references
Conversion of arable land to grassland	Likely positive, mostly based on indirect evidence	Meta-analysis	Overall probably positive, but little direct evidence on conversion. Will depend on intensity of grassland management. Indirect evidence that grasslands have more biodiversity than arable fields (Tsiafouli *et al*. (2015), but this is not on conversion as such).	Spurgeon *et al.* 2013
Grassland management for biodiversity	Grazing: positive Mowing: positive Fertilisation: negative	Literature reviews	Avoid afforestation of semi-natural grasslands.	Habel *et al*. 2013; Plantureux *et al*. 2005; Tälle *et al.* 2016; Wang and Tang; 2019 Many examples in older literature.
Agroforestry	Positive (+61%)	Meta-analysis	Results vary depending on agroforestry practices with smallest effect found for silvopastures (+9%) and largest for shaded perennial systems (+86%) (Beillouin *et al.* 2021). Heterogenous on average positive effects. May need a longer timeframe for full effects.	Beillouin *et al*. 2021. Torralba *et al*. 2016. (But see Mupepele *et al*. (2021) for a smaller positive effect.)
Hedgerows, woody buffer strips, farmland trees	Positive but variable	Literature review	Variable results, no explicit meta-analysis found.	Montgomery *et al.* 2020.
Increased diversity in crop rotation (improved crop rotations)	Positive (+37%)	Meta-analysis		Beillouin *et al*. 2021
Crop diversity as cover crops	Positive (+21%)	Meta-analysis	Positive effects in recent studies. However, results not conclusive across studies because of a scarcity of data (Shakelford *et al*. 2019).	Beillouin *et al*. 2021 Kim *et al.* 2020
Crop diversity as intercropping	Positive (+7%)	Review, meta-analysis	Effects of intercropping on associated biodiversity relatively small and not always significant; using crop varieties neutral effects (both Beillouin *et al*. 2021).	Brooker *et al.* 2015; Beillouin *et al*. 2021
Minimised tillage: Reduced, minimum or no tillage	Mixed effects on different organisms, depending on soils, region, management, etc. Earthworms positively affected. Arbuscular mycorrhizal fungi.	Meta-analysis, field studies	Mixed results. Soil bacterial and faunal biodiversity (+7% and +28%, respectively) increases with reduced tillage, but no significant effects on fungi, arbuscular mycorrhizal fungi, or functional diversity (de Graaff *et al*. 2019). Minimal effects on soil microbiota (field study, Frøslev *et al*. 2021). Earthworm abundance and biomass positively affected (Briones and Schmidt 2017). Comment: a complex solution—variable effects and side effects: trade-off with herbicide use.	de Graaff *et al*. 2019 Frøslev *et al*. 2021 Briones and Schmidt 2017

Appendix 4 Evidence table for showing examples of diversification of agroecosystems at three major spatial scales (within-crop, between crops, landscape scale) and their effects on biodiversity, ecosystem services and yield

Scale of diversifi-cation	Diversification measure	Effect on biodiversity, ecosystem services and yield	Type of evidence	Remarks, trade-offs or synergies between biodiversity and production	Key references
Within-crop	Increasing crop genetic diversity in field, farm and landscape scales	Increasing crop genetic diversity is useful in pest and disease management, and has the potential to enhance pollination services and soil processes in specific situations.	Narrative review	No direct evaluation on agricultural production.	Hajjar *et al*. 2008.
Within-crop	Using crop variety mixtures	Crop variety mixtures can support pathogen resistance, yield stability and yield enhancement compared with monocultures. They often require lower level of input.	Narrative review	Despite the benefits of using crop variety mixtures, their development and use is challenging because of potentially undesired trait heterogeneity and uncertainties of the performance of the various mixtures.	Wuest *et al*. 2021
Within-crop	Using crop variety mixtures	A meta-analysis of 246 experiments on wheat and barley (Kiær *et al*. 2009) found a mean positive effect of crop variety mixtures on grain yield of 2.7%.	Narrative review (Barot *et al*. 2017), meta-analysis (Kiaer *et al*. 2009)	Mixing crop varieties can help overcoming trade-offs between soil fertility and yield compared with monocultures.	Barot *et al*. 2017; Kiaer *et al*. 2009
Between crops	Multiple diversification practices in cropping systems	Diversification practices in cropping systems at multiple spatial scales support biodiversity by 40%, pollination by 32%, pest control by 23%, while yield remains on a similar level.	Meta-analysis and systematic review of 98 meta-analyses	Synergy: diversification practices support biodiversity and ecosystem services and do not compromise yield.	Tamburini *et al*. 2020
Between crops	Combination of multiple diversification practices (rotation extension, intercropping, multiple cropping or multi-services cover crop)	The combination of diversification practices could improve the environmental performances while maintaining *a priori* economic and social performances at satisfactory levels	Primary article	Diversification may cause drawbacks for some indicators (gross margin, NO_3 lixiviation, NH_3 volatilisation or pesticide use) in some cases. The effect of a combination of diversification practices on an indicator depends on the pedo-climatic context.	Viguier *et al*. 2021

Scale of diversifi-cation	Diversification measure	Effect on biodiversity, ecosystem services and yield	Type of evidence	Remarks, trade-offs or synergies between biodiversity and production	Key references
Between crops	Cover cropscover crops	Cover crops increase soil organic carbon by 0.1–1 Mg/ha/yr depending on biomass, years in cover crops and initial soil carbon; decrease runoff by up to 80% and sediment loss by 40–96%; increase soil microbial abundance by 27%, activity by 22% and diversity by 2.5%. Other benefits: alleviate soil compaction, improve soil structural and hydraulic properties, recycle nutrients and suppress weeds.	Meta-analyses; Quantitative synthesis	Cover crops increase or have no effect on crop yields except in the case of reduced drainage (because of higher evapotranspiration) and higher yields in water-limited regions. Ecosystem services of cover crops can be promoted synergistically with services related to climate change mitigation and adaptation. However, results on increased GHG emissions are also reported under cover crops compared with fallow, probably because of increased microbial decomposition rates.	Blanco-Canqui *et al.* 2015; Kaye and Quemada 2017; Meyer *et al.* 2019; Daryanto *et al.* 2018
Between crops	Intercropping with leguminous crops	Cropping systems diversification through intercropping can be used for simultaneous production of both cereals and grain legumes, while increasing the use of nitrogen sources and reducing external inputs of nitrogen fertilisers. Intercropping can provide higher and more stable yield, improved weed and pest control, increased soil stability and higher soil biodiversity compared with sole crops.	Narrative review	No trade-offs between ecosystem services and yield have been mentioned.	Duchene *et al.* 2017

Scale of diversifi-cation	Diversification measure	Effect on biodiversity, ecosystem services and yield	Type of evidence	Remarks, trade-offs or synergies between biodiversity and production	Key references
Between crops	Intercropping with leguminous crops	Intercropping consistently stimulates complementary nitrogen use between legumes and cereals by increasing N_2 fixation by grain legumes and increasing soil nitrogen acquisition in cereals. Cropping systems diversification through intercropping can be used for simultaneous production of both cereals and grain legumes, while increasing the use of nitrogen sources and reducing external inputs of nitrogen fertilisers.	Meta-analysis on 29 studies	The results of the meta-analysis show that there is a great opportunity for intercropping systems containing cereals and legumes both for crop production and for nutrient cycling.	Rodriguez *et al.* 2020
Between crops	Within-field crop diversification (polycultures)	Well-designed polycultures can produce win–win outcomes between per-plant and potentially per-unit area, primary crop yield and biocontrol. Biocontrol services are consistently enhanced in polycultures, so polyculture management that focuses on yield optimisation is likely to be the best strategy for maximising both services.	Meta-analysis of 26 studies	There is a win–win relationship between the per-plant yield of the primary crop and biocontrol in polyculture systems that minimised intraspecific competition via substitutive planting. Additionally, there is an improved biocontrol service with no difference in the per-unit area yield of the primary crop in polyculture fields at high cropping densities (additive planting) where legumes were used as the secondary crop.	Iverson *et al.* 2014
Landscape scale	Small field size	Farmland biodiversity is higher in fine-grain landscapes with small fields. Supporting and regulating ecosystem services (pollination, pest control) are larger in landscapes with small fields. Decreased economic profit (cultivation is less cost-effective compared with large fields).	Narrative review	There is a trade-off between diversity and profit; but this can be addressed by (1) technological innovations to reduce costs of cultivating smaller fields; (2) market rewards and (3) subsidies for smaller fields; (4) decreasing input and taking advantage of biodiversity-mediated ecosystem services.	Clough *et al.* 2020

Scale of diversifi-cation	Diversification measure	Effect on biodiversity, ecosystem services and yield	Type of evidence	Remarks, trade-offs or synergies between biodiversity and production	Key references
Landscape scale	Grassland–forest mosaic	The availability of shrubs within or close to calcareous grasslands supports grasshopper species (see Poniatowski and Fartmann 2008), above-ground nesting wild bees and bumble bees (see Steffan-Dewenter and Tscharntke 2002) and several rare or red-listed butterfly species (see Ouin *et al.* 2004; Fartmann 2006). An intermediate (≥15%) cover of woody species supports the best the red-listed invertebrates (see Gallé *et al.* 2017) and birds (see Pärt and Söderström 1999) in pastures or meadows.	Primary articles	An intermediate cover of woody species on pastures can support biodiversity without large decrease in the utilised (mown or grazed) grassland area.	Poniatowski and Fartmann 2008; Steffan-Dewenter and Tscharntke 2002; Ouin *et al.* 2004; Fartmann 2006; Gallé *et al.* 2017; Pärt and Söderström 1999
Landscape scale	Diversification of temporal grassland with forage legumes and herbs	The use of forage legumes and herbs in temporary grassland swards is a promising strategy to enhance productivity and species diversity in forage-based low-input dairy production.	Primary article and review article	Synergy: win–win for biodiversity, ecosystem services and yield quality.	Hamacher *et al.*; 2021;; Lüscher *et al.*; 2014
Landscape scale	Establishment and management of vegetated strips	Vegetated strips adjacent to farmed fields (field margins, buffer strips, hedgerows) can increase biodiversity, nutrient retention, improve hydrological regimes, adsorb toxic substances, protect neighbouring areas from erosion, deflation, control pests and increase carbon sequestration.	Systematic map database	Different strip types can produce multiple benefits, none can wholly provide for all environmental outcomes. Benefits can be optimised by adjusting management practices according to the purpose. There can be trade-offs: e.g. vegetated strips aiming at buffering pollution can have reduced biodiversity benefits due to the accumulation of pollutants within the strip.	Haddaway *et al.* 2018

Scale of diversifi-cation	Diversification measure	Effect on biodiversity, ecosystem services and yield	Type of evidence	Remarks, trade-offs or synergies between biodiversity and production	Key references
Landscape scale	Structural heterogeneity within, around and between grasslands	Historic management has created heterogeneity at three scales (within, around and between grasslands) and many species depend on this structural diversity. To conserve the full range of biodiversity associated with calcareous grasslands, conservation management should aim at increasing heterogeneity in, around and between grasslands.	Narrative review	Conservation priorities: (1) creation of heterogeneity by reintroducing diverse land-use patterns (e.g. combination of grazing and mowing, mosaic management); (2) developing a regional management system for areas surrounding the grasslands to increase the availability of edge habitats; (3) increase the heterogeneity of diverse interstitial elements to effectively facilitate the movement of species leading to functional connectivity.	Diacon-Bolli *et al.* 2012

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