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July 2020

EXPERT BRIEF

SOIL

FiBL's contribution to the ESAD EU platform

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Suggested citation:

Mäder, P and Bünemann, E (2020) Soil. Expert brief submitted to the European Sustainable Agriculture Dialogue, FiBL.

FiBL

SUMMARY

European soils are under threat, with loss of soil organic matter and biodiversity among the most serious pressures.

This paper gives an overview of past and ongoing EU funded research projects in the field of multi-functionality of soils, with a focus on soil organic carbon and biodiversity, and highlights key findings.

Research gaps are identified and propositions made for further research at the European level to achieve sustainable soil use and to promote the application of promising management practices.

ACKNOWLEDGMENTS

The European Sustainable Agriculture Dialogue (ESAD) is a multi-stakeholder platform created in 2019 that brings together 35+ key actors from across society – including industry, civil society, universities, and research centres – to discuss key topics, exchange views and standpoints, and recommend research needs to achieve sustainable agriculture.

ESAD is grateful to Paul Mäder and Else Bünemann (FiBL) for their outstanding work the past months to draft this paper. As an independent and external researchers to the ESAD group, they have provided an evidence-based and balanced perspective on the matters explored in this paper.

Selected members of the ESAD community, as part of a Task Force, were consulted and their inputs were taken into account by the external expert in the drafting process.

The paper does not reflect the views and opinions of single ESAD members that were consulted. As such, their contribution is not to be interpreted as an endorsement of the final paper.

European
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INTRODUCTION

Soils are pivotal for all life on earth. Currently soils are under threat, and soil quality and biodiversity are decreasing. Decline of soil organic matter, biodiversity loss, erosion and compaction, as well as contamination are among the most severe pressures on soil originating from unsustainable land management.

Bünemann et al. (2018) reviewed existing soil quality concepts worldwide and pointed out the **multi-functionality of soils** and provision of essential ecosystem services **(Figure 1)**. Soils produce biomass for food, feed, fibre and energy, conserve biodiversity, regulate the climate through carbon sequestration, and control pests and diseases. A healthy soil is also less prone to erosion due to its better infiltration and stable aggregates, and soils filter our drinking water.

Sustainable management of soils plays a key role in keeping within the safe operation space of the planetary boundaries (Steffen et al., 2015) and may as such help to frame research and innovation activities by the European Commission. Besides biodiversity loss and nutrient flows due to excessive use of N and P fertilizers, climate change and land use change may already be in the zone of increased or high risk (Figure 2).

Soils are a major sink for CO_2 from the atmosphere, and thereby mitigate **climate change.** On the other hand, soils are also a major source of greenhouse gas emissions (nitrous oxide, methane and CO_2). While N input and anoxic conditions are key drivers of N_2O emissions, the major source of soil-derived CH_4 are paddy rice fields (apart from ruminants). Soil organic carbon is mineralised constantly, but especially after deep inversion ploughing, and a lot of CO_2 is released after land use change from natural grassland or forests to cropland. In this respect, the 4 per 1000 initiative propagates to increase carbon sequestration of soils by appropriate management practices, e.g. afforestation, ley crop rotation, mixed cropping, reduced tillage and the application of biochar.

Agricultural systems and management such as the application of pesticides and excessive use of fertilizer (N, P) as well as **land use change** affect above- and below-ground **biodiversity** directly (Bardgett et al., 2014), and indirectly as nutrient losses from agricultural land impact biodiversity in natural ecosystems.

Thus, sustainable management of soils is an imperative to keep our planet healthy.

Soil based ecosystem services are closely linked to the **sustainable development goals** of the United

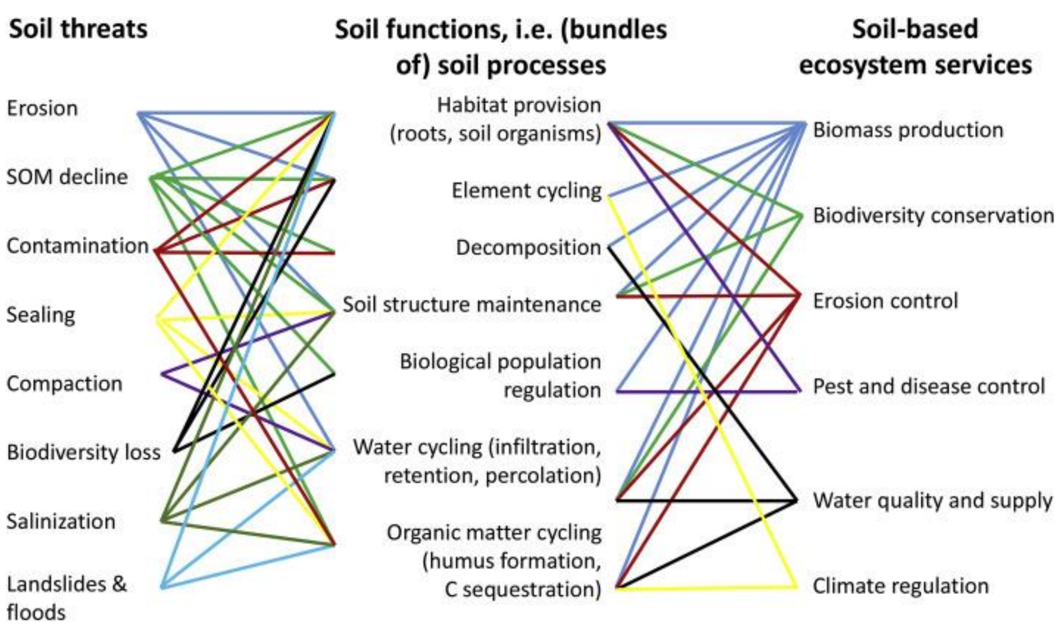


FIGURE 1
Linkages between soil threats, soil functions and ecosystem services. Bünemann et al. (2018)

Nations (SDGs), and there is ample evidence that soils contribute to most of the 17 SDGs (Smith et al. 2019), in particular to SDGs 2) Zero hunger, 6) Clean water, 12) Responsible consumption and production, 13) climate action and 15) Life on land. SDG 15 "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" has specific reference to soils. Target 15.3 aims to "combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world" by 2030.

The European Green Deal is an integral part of the European Commission's strategy to implement the United Nation's 2030 Agenda and the SDGs and sets the roadmap for making EU's Economy sustainable.

This will happen by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all. Several elements of the strategy are targeting the sustainable use of soils:

1. "Zero pollution ambition for a toxic free environment",
2. "Preserving and restoring ecosystems and biodiversity",
3. "From farm to fork: a fair and healthy and environmentally friendly food system", and
4. "Increasing the EU's climate ambition for 2030-2050".

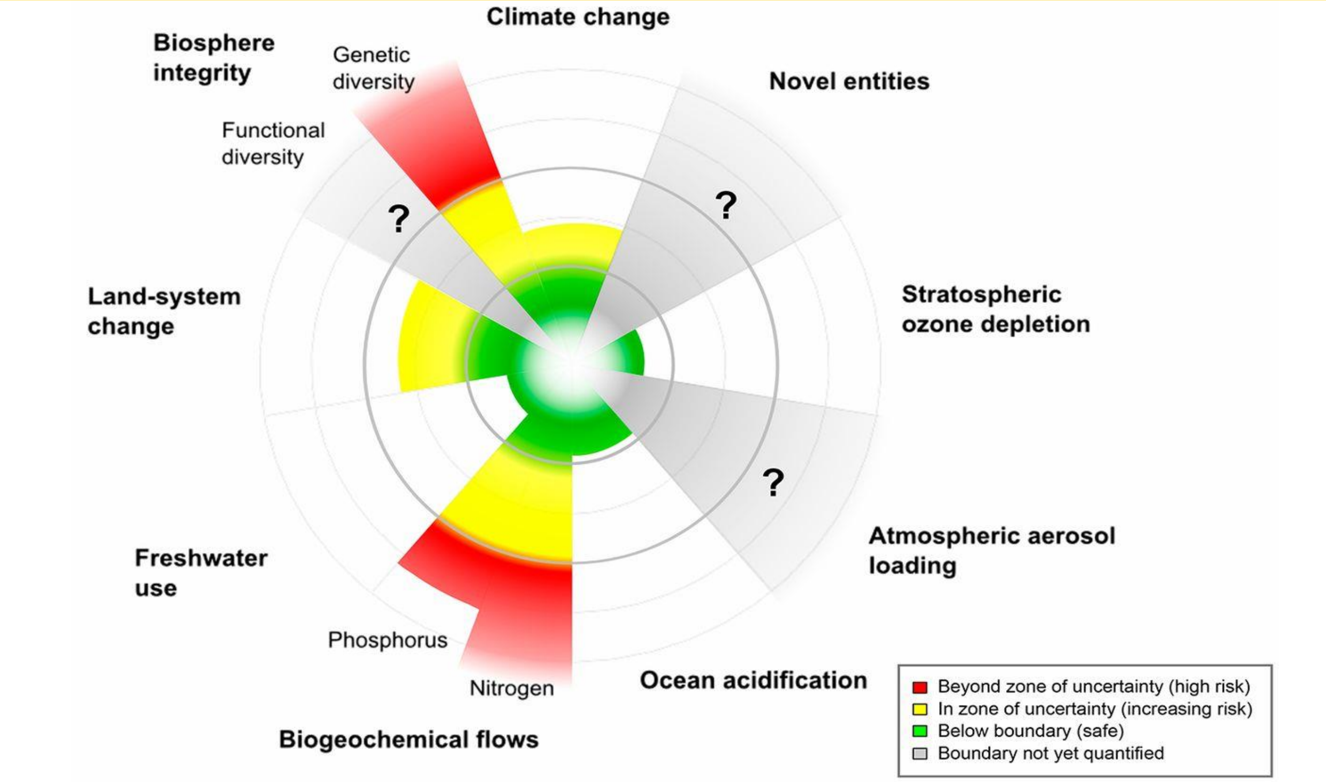
For the new Horizon Europe, "Soil health and Food"[i] is considered as a mission priority, aiming at providing a powerful tool to raise awareness on the importance of soils, to engage with citizens, create knowledge and develop solutions for restoring soil health and soil functions. At the same time, this will allow full use of the potential of soils to mitigate and adapt to the effects of climate change.

This paper will focus on agricultural soil health and linkage to climate change and biodiversity research.

It will identify gaps and provide recommendations for further research with potential to support and accelerate delivery of the Green Deal.

FIGURE 2

Planetary boundaries: Guiding human development on a changing planet. Steffen et al., 2015.



1. CURRENT KNOWLEDGE AND SUMMARY OF EXISTING KNOWLEDGE

In this chapter, past and current EU funded research projects in the field of multi-functionality of soils, climate regulation through carbon sequestration, biodiversity, and soil health are described in brief.

Table 1 highlights the focal points of the selected projects in these areas. The various projects put a different weight on soil threats, sustainable management and nutrient management options. The development of tools and indicators to assess soil quality and to calculate the economic viability of sustainable management options are also emphasised in this table. Modelling of soil properties and functions is key for upscaling at national, EU and global level (Table 1).

Several aspects of the food system are not addressed in this research summary, because they are broader systemic issues that require a more cross-sectoral and interdisciplinary research focus: 1) The impact of food diets on soil use and soil health: to produce less grains for animal feeding coupled with less meat consumption reduces the pressure for intensification of agricultural production, clearance of natural forests and grassland-conversion for cropping; 2) The reduction of food waste to reduce pressure on land use change for agriculture; 3) The positive effect of the combination of livestock systems based on roughage feed and arable crops with respect to soil health and biodiversity. Similarly, projects aiming at improving grassland production (e.g. GRASSMARGINS, 2011-2015, and Inno4Grass, 2017-2019) typically had a minor soil component that is not included here due to time and space limitations.

Summary of existing research and conclusions

This chapter sums up EU funded research activities in the area of soil in the past decade. It follows the structure of Table 1, in which the projects are listed and their activities are weighted with respect to various aspects. We refer to Annex 1 for a more detailed description of key EU-funded research projects with aims, methodological approaches and major research findings including references.

Healthy soils provide a multitude of functions essential for sustainable agriculture. While yield was for decades considered as the main indicator for fertile soil, **the concept of soil multi-functionality** has gained considerable interest in the last decade. Healthy soils provide a wide range of soil functions and thereby soil based ecosystem services.

Soil health and soil quality were addressed especially in the projects iSQAPER, LANDMARK, FertilCrop and RECARE, going from literature review and further development of the conceptual basis to the development and application of methods to assess soil health and soil quality by indicators (Table 1).

While the RECARE project dealt mainly with **soil threats and restoration of degraded soil**, the other projects focused more on soil functions. The new SPRINT project will look at soil health as affected by plant protection products (PPPs) and develop pathways to a more sustainable plant protection, and it aims to develop a Global Health Risk Assessment Toolbox to assess impacts of PPPs on environment and human health.

The concept of multi-functionality of soils is now widely accepted in the scientific community but has not yet reached all the different stakeholders. Therefore, there should be an attempt to bring the existing knowledge and awareness of the various soil functions to farmers, extension services and policy makers. Although specific soil management practices may simultaneously favour various soil functions, e.g. carbon sequestration, biodiversity maintenance or water provisioning, other functions may be affected in the opposite direction, e.g. yield versus carbon sequestration and biodiversity. Thus, innovative measures to improve yield without hampering biodiversity are needed, e.g. by agro-ecological measures like applications of green manures or biofertilizers. Although a set of analytical and visual soil quality assessment tools guaranteeing multi-functionality has been identified, application in extension, soil monitoring programs, and land use planning is limited. Building the new mindset through education at all levels, and targeted campaigns for awareness building of soil functions are considered essential.

Several EU research projects tackled how soil quality and soil functions are affected by **sustainable management options** (iSQAPER, CIRCASA, SoilCare and LANDMARK). It was found that a series of farming systems and management options, such as crop rotation, reduced tillage, the addition of organic matter and organic agriculture positively impact multiple functions of soils. The LANDMARK project developed a concept whereby a farmer or advisor can rate the importance of five soil functions on a given field and prioritize which functions to improve through management. At the same time, management options need to be tailored to pedo-climatic site conditions, as found in iSQAPER, and there is a need to further develop the knowledge of which management options perform best under which soil and climatic conditions.

Management options to maintain and restore degraded soils caused by specific soil threats have been identified to a large extent. However, adoption of these sustainable management options by farmers is often limited. There is a multitude of reasons for that: the need to invest in new machinery and technologies, lack of knowledge, risk of crop failure, economic and societal barriers, traditions, logistical bottlenecks like lack of collection centres and processing units, and market options. Thus, optimisation of the production needs a careful identification of soil threats to be combated and desired soil functions to be improved. Thereby a thorough consideration of the complete downstream and upstream value chain of food production has to take place. It becomes obvious that further research should be directed towards implementation of sustainable management options, and towards policy instruments which can combat the impeding factors for adoption and strengthen the promoting factors. A strong focus should be put also on knowledge barriers, because many sustainable management options such as organic agriculture, no-tillage, agroforestry, mixed cropping and permaculture are knowledge-intensive.

The issue of soil organic matter loss was addressed in CIRCASA, TILMAN-ORG and Eco-Serve. Afforestation or reforestation, wetland restoration, soil carbon sequestration, biochar and bioenergy with carbon capture and storage were found to be effective **for greenhouse gas removal** from the atmosphere **through carbon sequestration** (CIRCASA). Still, the question of carbon capture across the whole soil profile is disputed, because many studies only assessed carbon stocks or relative carbon concentrations in top soil layers, and soil organic carbon exhibits large spatial heterogeneity. Soil organic carbon in form of organic matter or humus affects most soil functions and sustainability goals positively according to a large review made in CIRCASA. However, there were also some negative effects. Among the barriers for more adoption of carbon sequestration options, economic barriers are of great importance, but also knowledge barriers and political priorities related to financial incentives, like carbon credits and subsidies (CIRCASA, TILMAN-ORG). Moreover, constraints between ecosystem services exist.

For instance, reduced tillage and organic farming often increased soil organic matter and soil biological activity and biodiversity, but yields were lower than in plough systems and conventional agriculture, respectively (iSQAPER, TILMAN-ORG). Another constraint is the positive effect of no-tillage on soil life and soil structure, but its practice is regularly associated with the use of broad-spectrum herbicides, such as glyphosate. This herbicide and its metabolite AMPA belong to the compounds most frequently found in soils (Silva et al., 2018; 2019), and is often found in groundwater (Battaglin et al., 2014). It is also important to differentiate between short-term and long-term effects: in the short term, intensive conventional agriculture can boost yields and profitability, but in the long-term, soils may degrade, and be lost e.g. through erosion (Pimentel et al., 1995).

To conclude, practices to improve soil organic carbon are known to a large extent, however, adoption of these practices is slowed down by technical, economic and institutional reasons. Tradition and skills of farmers also play a major role. For those practices that can negatively affect soil functions other than carbon sequestration, such as food production, a careful testing is needed. Although, at large scale, a prediction of soil carbon development by models seems possible, it is still difficult to measure the development of soil organic carbon over time at field scale due to small-scale spatial variation and heterogeneity in soils. Under these conditions, subsidy schemes need to be based on the fulfilment of specific management practices with a proven impact on soil organic carbon in long-term experiments and surveys, rather than on measured changes in a field over a relatively short time.

Resistance and resilience to climate change has been addressed in two Biodiversa projects, EcoServe and SoilClim. These studies found enhanced potential of organic and ecological intensive farming systems to resist drought through increased soil organic matter contents and a more diverse microflora compared with conventional systems. Provisioning of nitrogen and plant growth were enhanced in soils from field plots with long-term organic farming management history under water stress. Resilience is now the focus of two on-going projects (Diverfarming and SURE-Farm). While soils are not in the centre of these projects, the effects of the developed resilience framework (SURE-Farm) and the diversified agricultural systems (Diverfarming) on soil quality and soil health are taken into account. To conclude, research dedicated to resilience and resistance to climate change is still limited, but it seems that ecological intensive farming leads to more resilient systems. There is a need to further increase our knowledge on how to create more resilient systems under different pedo-climatic conditions in order to adapt the European Agriculture to climate change.

Biodiversity in soils is impacted by chemical and physical soil properties and climate, but also by management (iSQAPER, Eco-Serve, Diverimpacts, Diverfarming, EcoFINDERS, LANDMARK). Management was shown to affect soil microbial communities, with higher biomass and catabolic activity in ecological (organic) systems than conventional systems (Eco-Serve). Crop traits have distinct effects on soil organic matter contents and quality. It was found that differences in soil microbial composition affect soil biogeochemical cycling. The presence of arbuscular mycorrhizal fungi resulted in less N and P losses under climate change scenarios. Proteolytic microbial communities in organically managed soil were shown to be able to maintain biodiversity under extreme drought events, whereas proteolytic microbial communities in conventionally managed soil could not. Moreover, soil organic matter was shown to positively affect biodiversity (SoilClim). A meta-analysis conducted in Diverimpacts revealed that rotation and intercropping are associated with increased yields, while agroforestry improves soil quality and biodiversity. Overall, above and belowground biodiversity seems to render agricultural systems less prone to stresses and more resilient to climate change (EcoFinders).

Furthermore, there is clear evidence that specific farming systems and management practices such as organic agriculture, agroforestry, and crop rotation enhance biodiversity below and above ground. Because a wealth of insects lives at least for parts of their reproduction cycles below ground, soil management plays a crucial role also for above ground biodiversity. Along the food web, birds and mammals may also be indirectly affected by soil management. Apart from biodiversity management in fields, landscape patterns and regional land use strongly affect areas under agricultural use. Combined approaches therefore have the greatest potential to maintain and restore biodiversity.

Several ongoing projects focus on **the area of nutrient management** (LEX4BIO, FAIRWAY, CIRCULARAGRONOMICS, NUTRI2CYCLE). While FAIRWAY is working on nitrate and pesticide leaching, the other three projects concern nutrient recycling technologies that will enable a more circular economy. In this area, more work is certainly needed, and trade-offs with respect to soil quality and soil health need to be examined closely, e.g. with respect to soil organic matter management and soil contamination with inorganic and organic pollutants as well as microplastics.

Interactive tools (e.g. smartphone applications) to assess soil threats, soil health and the economic viability of sustainable management options were developed in iSQAPER, LANDMARK, FertilCrop and SoilCare in particular. Special attention was paid to visual assessment methods of soil health applicable in the field by farmers and extensionists (iSQAPER, FertilCrop). The smartphone application SQAPP developed by iSQAPER makes global soil and landscape data freely available and provides site-specific interpretation of widely used soil quality indicators, assesses the local threats to soil quality and gives recommendations for soil-improving management practices. A decision support system for simultaneously assessing and improving the supply of several soil functions was developed in LANDMARK. An interactive tool to assess the potential for application and the potential impact of soil-improving cropping systems is still under development in SoilCare. To sum up, a great number of tools to optimise soil management exists. Often these tools need further development after the end of the specific project in which they were developed, but a further improvement in follow-up projects is considered as not innovative. Solutions are needed to make such tool development more sustainable.

Many projects use **modelling and/or upscaling** in some ways, e.g. to extrapolate results from case studies to the entire EU. In iSQAPER, for example, the effects of widespread adoption of different types of agricultural management practices on soil quality were predicted in such a way. In LANDMARK, optimised scenarios for functional land management were modelled.

Almost all projects have a **policy component**, but several projects have a stronger emphasis. LANDMARK produced 11 policy options for functional soil and land management. FAIRWAY provided reviewed policies regarding the protection of groundwater and is now developing them further. LEX4BIO aims to provide the knowledge basis for future legislation on bio-based fertilizers. SURE-Farm is developing resilience-enhancing policies.

The **multi-stakeholder approach** was successfully used in several projects. LANDMARK, FAIRWAY and DiverImpacts show the benefits of stakeholder involvement to develop solutions that can be put into practice and be accepted by the appropriate groups. Nearly all projects considered multi-stakeholder involvement to a certain extent. The involvement of farmers is extremely useful, but in some cases, farmers involved in research projects have a high education level and may not represent the typical farmer in a region. Methods for self-empowerment of ordinary farmers may thus be most relevant in future.

Project	Soil multifunctionality	Climate regulation (Carbon sequestration, greenhouse gas emissions)	Resilience to climate change	Biodiversity	Soil health and soil quality	Soil threats	Sustainable management options/land use change and soil restauration	Nutrient management	Tool development/indicators	Modelling/up-scaling	Policy	Multi-Stakeholder approach
iSQAPER	xxx	x		xx	xx	xx	xxx		xxx	xx	xx	xx
CIRCASA	xxx	xxx	x	x	xx	xx	xxx	x	x	xxx	xx	x
TILMAN-ORG	x	xxx	x	xx	xx		xx	x		xx	xx	xx
FertilCrop	x	xx		xx	xxx	x	xxx	xx	xxx	x	x	xx
Eco-Serve	xx	xxx	xxx	xxx	xx	x	xx	xx	x	x	x	x
SoilClim	xx	xx	xxx	xxx	x	x	xx		x	x	x	x
Diverimpacts	x	x	xx	xxx	xx	xx	xxx	xx	xx	xx	xx	xxx
EcoFINDERS	xx	x	x	xxx	x	x	x	x	x		xx	
RECARE	x	x	x	x	x	xxx	x		x	xx	xx	x
SoilCARE	x	x	x	x	x	x	xxx	x	xxx	x	xx	x
LANDMARK	xxx	x		x	x		x	x	xxx	xxx	xxx	xxx
LEX4BIO		x		x	x		x	xxx			xxx	
FAIRWAY							xxx	xxx	x	x	xxx	xxx
DiverFarming	x	xxx	xx	xxx	x		xx	x		x	xx	
SPRINT	x			xx	xxx		xxx		xx		xxx	xxx
CIRCULARAGRONOMICS	x	xx	xx	x	x		x	xxx	x	x	xx	xxx
NUTRI2CYCLE	x	xx	x	x	x		x	xxx	xx	x	x	xxx
SURE-Farm	x	x	xxx	x	x		x		xx	xx	xxx	xx

LEGEND

Empty field: subject not covered in the project; x of low priority, xx of intermediate, xxx of high priority in the respective project

TABLE 1

EU funded projects in the field of soil and their relations to soil functions, carbon sequestration, biodiversity, soil threats and sustainable management options.

2. RESEARCH GAPS AND UNANSWERED OVERARCHING AND HIGH-LEVEL RESEARCH QUESTIONS

The **"European Green Deal"** is a central strategy of the European Union to implement the Sustainable Development Goals (SDGs) set by the United Nations with a strong focus on climate but also partly on biodiversity.

The **"Farm to Fork Strategy"** is at the heart of the Green Deal. It aims to comprehensively address the challenges of sustainable food systems and recognises the inextricable links between healthy people, healthy societies and a healthy planet. It points out that the increasing recurrence of droughts, floods, forest fires and new pests are a constant reminder that our food system is under threat and must become more sustainable and resilient. According to this strategy, there is an urgent need to reduce dependency on pesticides and antimicrobials, reduce excess fertilisation, increase organic farming, improve animal welfare, and reverse biodiversity loss.

The biodiversity crisis and the climate crisis are intrinsically linked. Climate change accelerates the destruction of the natural world through droughts, flooding and wildfires, while the loss and unsustainable use of nature are, in turn, key drivers of climate change.

Thus the **"EU Biodiversity Strategy for 2030"** is crucial both for halting the loss of biodiversity, but also to mitigate climate change and to adapt agricultural systems to climate impact. The five main direct drivers of biodiversity loss are: 1) changes in land and sea use, 2) overexploitation, 3) climate change, 4) pollution, and 5) invasive alien species. Biodiversity loss and ecosystem collapse are one of the biggest threats facing humanity in the next decades. Biodiversity loss may result in reduced crop yields and fish catches, increased economic losses from flooding and other disasters, and the loss of potential new sources of medicine.

Below, we have elucidated nine topics of the Farm to Fork and Biodiversity strategy 2030 with a close link to soil use and management, and have ordered our suggestions for research gaps according to the identified areas of these two EU strategies.

1. Ensuring food security and sustainable nutritious and affordable food

Healthy soils are the basis for sustainable food production. Previous research at the European level revealed that some farming systems and management practices have contradicting effects on ecosystem services. For example, organic farming and no-tillage or reduced tillage systems may favour carbon sequestration and erosion control, but often show lower yields. Weeds may become a problem and compete with crops due to lack of control through ploughing in organic reduced tillage systems and by herbicide resistance in conventional no-till systems. Future research should focus on the implementation of practices which help to boost yields in organic and no-till systems without jeopardising other soil-based ecosystem services.

As a promising future research approach, we suggest optimising cropping systems by combining sustainable agricultural practices, e.g. reduced tillage without the use of herbicides in organic farming, or reduced amounts of pesticides in conventional farming.

Additionally, principles of agro-ecological approaches may be used, resulting in optimal yields, high capacity of a soil to regulate pest and diseases, sequestering carbon across the whole soil profile, emitting little greenhouse gases, maintaining a high biodiversity, providing drinking water of excellent quality low or free in pesticides, and a good capacity to regulate erosion.

A lot of work has been done on tools to assess sustainable farming systems at field scale and in the lab. These tools need to be developed further and applied.

Specific components to develop such systems are:

- **Proper residue management**, diverse crop rotation and green manures.
- **Use of recycled fertilizers**, such as compost, liquid and solid digestates.
- **Modern techniques such as precision farming** and robotics, and new seeding technologies as aids for sustainable soil management and weed control.
- **Synergies with livestock production** through integration of leys (e.g. grass-clover mixtures) in the rotation, which improve soil structure, soil organic matter and accumulate nitrogen thanks to N-fixing bacteria.

A special focus shall be set on soil-, rhizosphere- and phyllosphere microbiome as related to plant health and human health:

- **Soils and in particular the rhizosphere** are populated by billions of microorganisms in one gram of soil, like bacteria, fungi, and protozoa. It has been shown that these associations can activate defence reactions of plants against pests and diseases, and improve macro- and microelement content and secondary metabolites of plants. Nutritious plants are essential to control cardio-vascular diseases, one of the biggest health burdens in the Western world. There are two options to enhance the soil microorganisms, management of indigenous microorganisms, e.g. by organic fertilisation, cover crops, mixed cropping, or inoculation of selected cultivated strains. Crop and soil specific inoculi have to be developed for maximum benefits for plants and subsequently humans.
- **Identify linkages between soil health, plant health and human health.** Recent research has shown that the soil and phyllosphere microbiome can impact the gut microbiome and health of mammals, and even the brain health. First results show that some soil-borne microbial strains have anti-inflammatory effect on brains under stress, and thus make mammals more resilient. At least this was demonstrated with mice. More ecological and clinical studies are needed with mammals for a mechanistic understanding of observed effects. It is important to conduct such studies also with humans to identify causal relationships between soil and plant microbiome and human health. It needs to be shown how soils shall be managed to generate a healthy soil microbiome with positive effects on physical and psychical health of humans.

2. Uptake of agroforestry measures should be increased as it has great potential to provide multiple benefits for biodiversity, people and climate

Agroforestry systems have a proven positive effect on soil health, in particular on biodiversity and soil organic matter.

To date, many agroforestry systems consist of cereals combined with trees (e.g. walnuts, olives, fruit trees), and there is little research on other systems such as silvo-pastoral systems. Future research should develop agroforestry systems adapted to various soils and climates in Europe.

3. Preserving and restoring soil quality and functions

Horizon 2020 projects identified farming systems and practices, which maintain and promote multi-functions of soils, e.g. organic agriculture, no-tillage systems, crop rotation and organic amendments.

While organic agriculture provides a series of ecosystem services at a moderate to high level, conventional agriculture is more productive, but has often drawbacks in biodiversity, carbon sequestration and soil structure (erodibility) (Reganaold and Wachter, 2016).

Still, two concepts how to achieve optimal multiple ecosystem services at regional scale are debated:

1. **A more general eco-functional intensification** providing various ecosystem services evenly distributed in e.g. organic farming systems, or
2. **Highly productive conventional management** in some areas with nature conservation areas in between.

Moreover, high-input conventional agriculture may be productive in the short run but can lead to severe loss of soil due to erosion. One third of arable land has already been lost world-wide (Pimentel et al., 1995), and in Europe about 25% of soils show signs of erosion. Long-term experiments like the Rothamsted (UK) and the DOK trial (CH) have shown that only with organic plus mineral fertilisation, maximum yields can be achieved while at the same time maintaining soil organic matter. In regions where livestock integration and organic manure are difficult to establish due to lack of infrastructure, alternative recycled fertilizers may serve as substitute and help to close nutrient cycles between cities and rural areas.

Research findings from previous projects describe close relationships between management, soil health and plant health.

Future research should address the question of further trophic levels, i.e. the connection between plant health, animal health and human health. Moreover, there is increasing evidence that the rhizosphere microbiota can contribute to the plant defence against soil borne pathogens. It would be interesting to elucidate if the plant health status and its phyllosphere microbiome impact the health of animals and humans feeding on these plants (concept of one health) (see also point 1).

4. New EU carbon farming initiative/climate smart agriculture

Soils can sequester carbon that was assimilated as CO_2 by plants through photosynthesis and entering the soil via crop residues and manure. Research conducted in Horizon 2020 identified afforestation or reforestation, wetland restauration, soil carbon sequestration through improved management, biochar and bioenergy with carbon capture storage to be effective in removing greenhouse gas from the atmosphere.

These practices are of high interest to fulfil the 4 per 1000 initiative. Soils with a high organic carbon content also promote a higher biodiversity in soil and increase their water holding capacity. Furthermore, there is evidence that soils with a more diverse microflora are more resilient to drought.

We suggest the following research topics to be further addressed:

- **Soil organic carbon stocks** are often estimated without determination of soil bulk density and only for top soils (max. 0-30 cm). However, the lower soil layers (subsoil) may harbour the same amount of carbon stocks as the top soil. Thus, further studies are needed to assess carbon storage potentials in dependence of management practices down to at least 50 cm.
- **We need rapid and cheap methods** to measure soil organic carbon in the field and lab by high throughput methods.
- **We need databases across Europe** for reliable modelling of soil organic carbon stock development under various management and climate change scenarios.
- **For biochar, we need a serious risk assessment** for further regulation of its use as a soil improver. Risks include organic and inorganic pollutants. Moreover, the production of char from wood may compete with cropland.
- **Farming systems and practices to sequester CO2** such as reduced tillage and organic farming need to be optimised with respect to crop yield.

- Further studies on the resilience of carbon sequestering production systems to climate change are of interest.

5. Preservation of soil biodiversity, ensuring that Europe's biodiversity will be on path to recover by 2030

Former EU funded projects showed that below-ground biodiversity is enhanced by organic agriculture, agroforestry and more diverse crop rotation systems. Basic research also shows that above-ground biodiversity of grassland is increased through a high diversity of symbiotic root fungi (mycorrhiza) and *vice-versa*.

More diverse grasslands are characterised by a high biomass production, increased N and P use efficiency and less N losses via leaching and N_2O emissions.

Furthermore, healthy soils with a diverse microflora can better regulate soil borne diseases and have an increased capacity to form stable soil aggregates, a prerequisite for soil structure formation and erosion control. Moreover, diverse soils were more resilient to drought stress and proteolysis as the first step of mineralisation.

In future, the following research questions are of high priority:

- **The role of soil management in the decline of insects.** A wealth of insects live for at least parts of their reproduction cycle in soil, and may be impacted by e.g. insecticides and mechanical damage and disturbance.
- **Further development of mixed cropping** positively impacting soil. In this respect it has to be kept in mind that more than 30% of photosynthates are entering the soil, feeding soil life. Which are ideal mixtures, with respect to yield, food and feed quality, and in view of feeding the below ground biomass of soil organisms?
- **Specific herbal varieties have multiple functions** at various trophic levels. For example, some plants excrete organic compounds that act as a nitrification inhibitor in soil, and thus reduce nitrate leaching and N_2O emissions, while serving as feeding source for insects and pollinators, and reducing methane emissions of ruminants. Therefore, developing more diverse feed and food mixtures with multi-functions in soil is a promising option to improve the nutrient efficiency and biodiversity of agro-ecosystems.
- **Although a lot is known on rhizosphere and bulk-soil biodiversity,** there is still a knowledge gap on how plants steer soil processes *via* their microbiome in soil, and how it can be positively influenced by management and inoculation. Past research has shown that inoculation of beneficial microbes is particularly efficient in Mediterranean and in dry tropical climates, and for soils that are low in soil organic matter (Schütz et al., 2018). Thus, it is necessary to elucidate under which conditions inoculation is promising in other climates.
- **Grassland soils are becoming more prone to erosion** and landslides in hilly regions. The question is which grazing systems and plant mixtures ascertain deep rooting and provide at the same time an optimal fodder quality, while still contributing to biodiversity?

6. Pollution of soils by pesticides and plastics, reduction of pesticides by 50% by 2030

Research in Horizon 2020 showed positive effects of organic agriculture on soil functionality.

- **One option for further research is to translate techniques** applied in organic agriculture to conventional agriculture (mechanical weed control, green manures, mixed cropping, grass-clover leys) and to develop integrated plant production systems with reduced pesticide input.
- **Studies to identify the effectiveness** and viability of techniques with potential to replace chemical pesticides in organic and conventional systems, especially in soil health terms.
- **Reports on the widespread presence of plastic particles** in the environment have raised concerns about whether these particles could be

taken up by plants and end up on our plates. An experimental study now reveals a mechanism through which nanoplastics can make their way into plant roots (Rillig, 2020). Thus, there is an urgent need to replace plastics, either by fully decomposable mulches (e.g. based on stark or lactic acid), or by mulch farming, covering the soil by living mulch or plant residues.

7. Reduce nutrient losses by at least 50%, reduction of fertilizer use by 20%, while ensuring that there is no deterioration in soil fertility

Nutrient surpluses are the main reason for eutrophication of ground and surface water and nitrous oxide emissions; furthermore, nutrient surpluses contribute to the decline in biodiversity.

A series of projects is ongoing to identify alternative fertilizers, and to develop more targeted application of fertilizers. In this area, research should focus on:

- **Closing nutrient cycles** between cities and rural areas.
- **Developing natural nitrification** inhibitors instead of chemical ones.
- **More strategic use** of green manures and mixed cropping with legumes.
- **Soil analyses** in the field by (remote) infrared sensors and adjusted fertilisation.
- **Steering soil** N mineralisation by targeted shallow harrowing.

8. Measuring outputs – solving problems on the ground

A multitude of tools to assess soil quality and for strategic planning of management practices has been developed in previous Horizon projects: decision support tools, models, practical guidelines for nutrient budgeting and carbon balances, etc.

Nonetheless, there are gaps for measuring system outputs and to monitor soil quality as affected by improved management: indicators for the amount and quality of soil organic matter in view of the soils to guarantee multi-functionality, high throughput molecular methods for measuring biodiversity in soil, and cheap and reliable spectroscopic methods for chemical and physical soil quality.

In particular, the following topics need to be addressed:

- **To bring existing tools** to real application in different pedo-climatic conditions and farming conditions (e.g. soil application: SQAPP, visual soil assessment: VSA, etc.).
- **Life cycle assessment** (LCA) methods/tools to evaluate sustainability of agricultural systems very often miss soil health and biodiversity, which gives an unbalanced picture. Therefore, it is essential to further develop LCA to include these areas.
- **Ensuring a more systematic match** of soil monitoring to the agricultural management practices used on that soil both for farmers and policy makers. This shall help to elucidate which management practices result in a good soil quality under certain pedo-climatic conditions.

9. Promote effective Agricultural Knowledge and Innovation Systems

An enormous body of knowledge has been generated in the past Horizon research projects. Still relatively little of the improved cropping systems has been taken up by farmers. Technical, societal and economic barriers were identified as hindering factors to implement promising management practices.

The following research and innovation activities are suggested:

- **How to improve farmer education** and to raise public awareness and acceptance of the importance of fertile soils and soil-based ecosystem services?

- **What are the current obstacles** for preventing implementation and what are strategies to overcome these?
- **How to develop effective policy schemes** to promote the adoption of sustainable management options (incentives, subsidies, taxes for critical inputs)?
- **Consumer purchasing trends, social pressure and perceptions** are an important aspect of the practical adoption of new practices. How to encourage adoption with a 'real-world' behavioural model in mind?
- **In-depth mapping of ongoing research** on soil quality are needed. Past and current management practices have to be recorded for the respective sampling sites to elucidate which practices lead to soils of high quality in various cropping systems and pedo-climatic zones.
- **To build on collective dissemination of knowledge** and co-learning practises between farmers, advisors and researchers.
- **To create awareness** for soils at all levels of education.

ANNEX 1: OVERVIEW ON PAST AND CURRENT EU RESEARCH PROJECTS IN THE FIELD OF SOIL

iSQAPER (2015-2020) aims to provide interactive soil quality assessment in Europe and China for agricultural productivity and environmental resilience, offering decision makers with science-based, easy to apply and cost-effective tools to manage soil quality and function.

Key findings of the project are:

1. Soils perform many functions, especially with respect to production, ecosystem- and climate-regulation (Bünemann et al., 2018). The quality of agricultural soils in particular is decreasing and is of concern at international levels (SDG, CAP, Soil Thematic Strategy, EEA).
2. Because of the heterogeneity of soil types, climate zone and farming systems, soil quality assessment and management need to target location-specific soil functions or soil threats.
3. To assess soil quality, an indicator set consisting of chemical, physical and biological indicators is recommended with guidance for the interpretation of indicator values. In addition to well-established indicators, promising novel ones include labile carbon and soil biological indicators (Bongiorno et al, 2019a; Bongiorno, 2019b).
4. Visual Soil Assessment (VSA) as wells as easy to measure soil properties allow for reliable frequent evaluation of soil quality at the farm level.
5. Results from long-term experiments as well as farm surveys reveal that management practices such as reduced tillage, organic agriculture, organic matter inputs and crop rotation positively affect soil quality, but with trade-offs between different ecosystem services (Bai et al., 2018).
6. The smartphone application SQAPP provides free and easy access to global soil and landscape data. It provides site-specific interpretation of widely used soil quality indicators, assesses the local threats to soil quality and gives recommendations for management practices that would improve it.
7. SQAPP is a useful tool for a wide variety of user groups including farmers, agri-advisors, researchers and policy makers, all of whom have been involved in its development and evaluation.
8. The concepts and principles underlying SQAPP are used to model the effects of widespread adoption of different types of agricultural management practices and show that even relatively low adoption rates of practices that improve soil quality could have a significant impact. The following items were identified as research gaps: data bases to collect soil data across Europe, high throughput analyses of soil biodiversity by molecular methods, and a mechanistic understanding of available carbon for soil functions and services.

CIRCASA (2017-2020) (Coordination of International Research Cooperation on Soil Carbon Sequestration in Agriculture) aims to develop international synergies concerning research and knowledge exchange in the field of carbon sequestration in agricultural soils at European Union and global levels, with the active engagement of all relevant stakeholders.

The team evaluated the following land management options for their potential for greenhouse gas removal (GGR): afforestation or reforestation (AR), wetland restoration, soil carbon sequestration (SCS), biochar, terrestrial enhanced weathering (TEW), and bioenergy with carbon capture and storage (BECCS) (Smith et al., 2019).

Risks and opportunities of these options were assessed in view of ecosystem services (Nature's Contributions to People; NCPs) and the United Nations Sustainable Development Goals (SDGs). It was found that all land-based GGR options contribute positively to at least some NCPs and SDGs. Wetland restoration and SCS almost exclusively deliver positive impacts. A few GGR options, such as afforestation, BECCS, and biochar potentially impact some NCPs and SDGs negatively, particularly when implemented at scale, largely through competition for land. For those that present risks or are least understood, more research is required, and demonstration projects need to proceed with caution (Smith et al., 2019). Suggestions were made how to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal (Smith et al., 2019) and how to quantify carbon for agricultural soil management from the current status toward a global soil information system (Paustian et al., 2019). In terms of barriers to implement carbon sequestration options, economic barriers are ranked very highly, followed by knowledge barriers (e.g. advisory services) and political priorities (also mostly related to financial incentives like carbon credits, subsidies etc.) (CIRCASA, 2019).

TILMAN-ORG (2011-2014) (Reduced tillage and green manures for sustainable organic cropping systems): the aims of the project were to design improved organic cropping systems with enhanced productivity and nutrient use efficiency, more efficient weed management and increased biodiversity, but lower carbon footprints.

It was found that yields were decreased by 8% under reduced tillage, and weed occurrence was enhanced. Soil organic carbon stocks in the topsoil were increased under reduced tillage compared with the plough systems (Cooper et al., 2016; Kraus et al., 2017, 2020). Soil organisms were favoured by reduced tillage. Further research and development are needed to synchronise nutrient supply and demand, to improve the machinery, and to adapt a farm-specific reduced tillage system to keep weeds controlled in the long-term without herbicides. Reduced tillage is advantageous especially for semi-arid regions.

Shallow ploughing is recommended in particular in the temperate zone, showing positive effects on soil organic carbon, without compromising yields and without increasing weed pressure. In humid climates, a hybrid system with reduced tillage and occasional ploughing (e.g. for ley destruction or in sandy soils) is promising, but effects on soil organic carbon need to be further studied. A new research area could be the in-depth analysis of the microbial response to tillage and pre-crops including green manures, which could be managed to optimise nutrient turnover in the future. In this approach, positive traits of weeds such as serving as a feed source for pollinators or beneficial insects, as well as negative traits were categorised and quantified for more than 150 weeds (Armengot at al., 2016).

FertilCrop (2015-2017) aimed at scrutinizing fertility-building measures and at evaluating the available tools to allow for the assessment of soil fertility. Close to hundred publications in form of peer-reviewed scientific articles, articles in agricultural media, farmer letters, videos and technical notes were produced in the frame of FertilCrop.

Weed pressure, weed seed decay and germination were investigated in trials (Rotchés-Ribalta et al., 2017) and the obtained data served to further increase the weed functional trait database (Bàrberi et al., 2018) commenced in TILMAN-ORG – the predecessor project. We tested practical tools to assess soil quality, among which farmers found the spade test most useful. The enhanced stratification of soils under reduced soil tillage is highlighting the role of the soil surface as the vital interface between the atmosphere and the management (Cania et al. 2020).

We reviewed the literature on N efficiency and means to reduce N_2O emissions and NO_3 leaching from organic arable crop rotations (Hansen et al. 2019), simulated crop- and soil N-dynamics and N_2O emissions in organic cropping systems and analysed scenarios to explore effects of fertility building measures (Doltra et al., 2019). Farmers and extensionists discussed the effectiveness of soil quality indicators during workshops and developed prototypes for organic soil management strategies.

FertilCrop had a large media coverage after its launch showing the great public interest (Fliessbach et al 2017). We produced videos and an interactive smartphone application in order to make the spade-test more popular and to facilitate its use.

Eco-Serve (Sustainable provisioning of multiple ecosystem services in agricultural landscapes, 2015-2017) aimed to evaluate alternatives to current agricultural systems that confer adaptation to the changing agro-ecological conditions due to increased rainfall variability under climate change.

A joint mesocosm growth chamber study based on soil monoliths extracted from differently managed fields (conventional-intensive *versus* ecological-intensive) across Europe and subjected to altered rain regimes was the central experiment of the project. Additionally, distinct research in relation to the joint mesocosm experiment based on literature work and experimental primary research was performed by each partner.

Some of the main Eco-Serve findings are that quality of crop litter, as determined by crop variety, and other organic soil amendments have a distinct effect on soil organic matter quantity (Garcia-Palacios et al., 2018), and quality (Martínez-García et al. 2018). Higher amounts of soil organic matter, higher concentration of dissolved organic carbon and lower aromaticity were found in ecological-intensive compared to conventional-intensive systems resulting in lower water repellence of the soil.

These observed effects are mediated by crop traits (e.g. leaf litter nitrogen concentration and root/shoot ratio), which differed considerably between crop varieties, and by soil management (García-Palacios et al. 2018). Management was shown to affect soil microbial communities, with higher biomass and catabolic activity in ecological-intensive systems than conventional-intensive systems (Lori et al. 2017).

Furthermore, differences in soil microbial composition resulted in less N and P losses (Martínez-García et al. 2017) and higher N provisioning in ecological-intensive management systems (Lori et al. 2020) under altered rain regimes.

Altogether, Eco-serve contributed to an increased mechanistic understanding of the interplay between crop litter quality and soil management in determining soil organic matter quality and quantity and how this affects water repellence and nutrient retention and supply of the soil.

SoilClim (2017-2020): Managing soil biodiversity and ecosystem services in agroecosystems across Europe under climate change.

SoilClim aims at improving our understanding of interactions between altered precipitation, soil organic carbon and biodiversity by conducting manipulative field experiments using rainout shelters (Kundel et al. 2018).

Rainout shelters were set up in arable fields managed either according to organic or conventional farming practises (Switzerland, long-term field experiment) and in agricultural field sites with contrasting SOC contents (Sweden, Germany, Spain; on-farm experiments).

While the data evaluation of these experiments is still ongoing, first results (Switzerland) indicate that the agricultural management plays a role for water storage at times of abundant rainfall which may help to replenish soil water before the onset of summer droughts. However, other measures specifically tailored to reduce soil water loss under drought will be needed in both farming systems.

Moreover, the abundance of arbuscular mycorrhizal fungi, which are essential plant symbionts with a central role for plant growth under drought, increased under the experimental drought and were especially enhanced in the organically managed soils.

The response of soil biodiversity and the associated functional attributes in the on-farm field experiments conducted across Europe was closely linked to ambient levels of precipitation. Across countries, soils with high organic carbon contents seem to take a positive effect on soil biodiversity, holding the potential to counteract adverse effects of future summer drought. A synthesis publication on the trade-offs and synergies between soil biodiversity and ecosystem services across countries is currently in preparation along with several, more detailed investigations on the drought effects on meso-and macrofaunal species.

DiverIMPACTS (2017-2022) - Diversification through Rotation, Intercropping, Multiple cropping, Promoted with Actors and value-Chains Towards Sustainability – is a multi-actor project of 34 partners in 11 European countries.

As modern agriculture in Europe is increasingly characterised by monocropping or short rotations, challenges like biodiversity loss, soil quality decrease and higher pest pressure demand for innovation.

Diversification of cropping systems aims to improve productivity, help deliver ecosystem services, and support the development of resource-efficient and sustainable value chains. With the focus on technical and organisational co-innovation in the frame of case studies accompanied by scientific research on the effect of crop diversification, DiverIMPACTS removes barriers along the value chain from farmers to consumers and creates strategies and recommendations to strengthen crop diversification practises on the long-term.

In a topical review, Beillouin et al. (2019) summarized 99 meta-analyses on crop diversification strategies. Rotation and intercropping are associated with increased yields while agroforestry improves soil quality and biodiversity.

EcoFinders (Ecological Function and Biodiversity Indicators in European Soils, 2011-2014) aimed to improve the knowledge on soil biodiversity and functioning with respect to ecosystem services. By sampling a European soil transect and five Long Term Observatories, the project found that soil biodiversity is driven primarily by soil physical chemical properties and thereafter by the land use (Plassart et al. 2019).

A set of cost-effective bioindicators was proposed (Griffiths et al. 2016), and Standardized Operating Procedures for soil sampling and assessment of soil biodiversity and functions were developed (Roembke et al. 2018). Tools to assess the economic value of soil biodiversity were developed, and the natural insurance value of biodiversity was stressed, which can increase resistance and resilience of the ecosystem.

The focus of RECARE (Preventing and Remediating degradation of soils in Europe through Land Care, 2013-2018) was on soil threats and on measures to prevent or remediate soil degradation across Europe. Indicators to assess soil threats were identified, and the status of the main soil threats in Europe was mapped based on data from the LUCAS sampling (e.g. Ballabio et al. 2018 on copper concentrations in topsoil). Measures to combat soil degradation were evaluated in a participatory approach and tested in case studies across Europe.

The effects of different prevention, remediation and restoration measures on soil functioning and ecosystem services were assessed (Schwilch et al. 2018). A spatial simulation tool to assess the cost-effectiveness of prevention, remediation, and restoration measures was developed.

Cost/benefit analysis revealed that some measures would be cost-effective both for farmers and for society, while others would need to be implemented through EU policies and strategies.

SoilCare (Soil Care for profitable and sustainable crop production in Europe, 2016-2021) investigates and promotes the use of Soil-Improving Cropping Systems (SICS) to improve soil quality and hence soil functions, while at the same time making cropping systems more sustainable and profitable.

The concept of SICS emphasizes the proper combination of crop rotations and management techniques such as tillage, fertilization, irrigation, drainage, pest, weed, residue and landscape management, depending on both socio-economic and environmental conditions (Oenema et al. 2017).

Therefore, SICS have been reviewed with respect to specific soil threats, e.g. salinization (Cuevas et al. 2019). Besides evaluating SICs at 16 study sites across Europe, the project has also reviewed the current structure and functioning of advisory services on sustainable soil management in Europe and identified a need to make policies and advisory services less fragmented and more effective (Ingram & Mills, 2019).

To synthesise and upscale the outcomes of the project, the team is developing an interactive tool to assess the potential for application and the potential impact of SICS throughout Europe.

LANDMARK (LAND Management: Assessment, Research, Knowledge base, 2015-2019) was a project on sustainable land management, aiming to develop guidelines on how to manage demands on land to deliver five soil functions, namely

1. food production,
2. carbon storage,
3. the provision of clean water,
4. habitats for biodiversity and
5. nutrient cycling.

The project worked on three different scales. On the local scale, i.e. for farmers and advisors, a decision support system for simultaneously assessing and improving the supply of several soil functions (www.soilnavigator.eu) was developed (Debeljak et al. 2019).

Based on data entered by the user, the current supply of the five soil functions is assessed, and management recommendations to improve specific soil functions as considered important by the user are given. On the regional scale, i.e. for legislators, soil monitoring schemes in Europe were reviewed with respect to indicators and sampling designs (van Leeuwen et al. 2017), and a monitoring approach for soil functions was developed and tested in a pan-European sampling campaign of arable and grassland sites.

At the policy level, the impact of current policies on soil functions was reviewed (Vrebos et al. 2017). Societal demands for soil functions across EU member states were mapped (Schulte et al. 2019), and optimised scenarios were modelled, resulting in 11 policy options for functional soil and land management.

LEX4BIO (Optimizing Bio-based Fertilisers in Agriculture – Knowledgebase for New Policies, 2019-2023) aims to reduce the European dependency on imported fertilisers by increasing the use of nutrient-rich side-streams like manure and sewage sludge as bio-based fertilizers in agriculture. In the project, nutrient-rich side-streams are mapped and technologies for producing safe fertilizers scrutinized.

Bio-based fertilizers are characterized with respect to nutrient content and availability as well as contamination with potentially harmful substances. By optimising the use of fertilisers according to crop requirements, their environmental impact can be minimised and profitability of agriculture improved.

The project will provide recommendations for decreasing the dependency on imported fertilisers, closing nutrient cycles, and improving the sustainability of European farming systems.

FAIRWAY (Farm systems that produce good Water quality for drinking water supplies, 2017-2021) focusses on diffuse pollution of nitrogen and pesticides from agriculture and thus indirectly also on the water purification function of soils.

The main objective is to review and further develop policy, governance and farm management approaches that protect drinking water resources in the EU. Multi-actor platforms deliver input to the assessment of water quality indicators, measures and practices to decrease nitrate and pesticide leaching, use of decision support tools, the assessment of governance arrangements, and stakeholder feedbacks on the case studies.

So far, two review reports on effective mitigation measures and practices to reduce nitrate and pesticide leaching, respectively, have been completed. A review on the use of fertilization planning and nitrogen budgeting at the farm level across Europe (Klages et al. 2020) revealed that nitrogen budgets have to be calculated in only 3 of the 14 studied countries, although they represent a very useful environmental indicator.

The outputs of the project will provide a blueprint for multi-actor engagement across different scales, which will allow addressing agriculture and water policies in an integrated way.

Diverfarming (Crop diversification and low-input farming across Europe: from practitioners engagement and ecosystems services to increased revenues and chain organisation, 2017-2022) aims to develop and deploy innovative farming and agribusiness strategies in order to increase the long-term resilience, sustainability and economic revenues of agriculture across the EU.

The diversified cropping systems are tested in field case studies for major crops within six pedoclimatic regions. The project has summarized existing data on diversified cropping systems and confirmed that diversified arable cropping systems in selected European regions increase soil organic carbon (Morugán-Coronado et al. 2020; Francaviglia et al. 2019, 2020).

The approach taken by the project should deliver:

1. increased overall land productivity;
2. more rational use of farmland and farming inputs (water, energy, machinery, fertilisers, pesticides);
3. improved delivery of ecosystem services by increments in biodiversity and soil quality;
4. proper organization of downstream value chains with decreased use of energy; and
5. access to new markets and reduced economy risks.

SPRINT (Sustainable Plant Protection Transition, start 2020) aims to develop a Global Health Risk Assessment Toolbox to assess impacts of Plant Protection Products (PPPs) on environment and human health.

It will inform integrated approaches to fully assess overall risks and impacts of pesticide formulations, residues and metabolites. Work will take place both at regional and European level, and the project will assess the environmental and economic sustainability of alternative strategies to pesticide use.

Thereby, the project will develop transition pathways towards more sustainable plant protection in a multi-actor approach.

CIRCULAR AGRONOMICS (Efficient Carbon, Nitrogen and Phosphorus cycling in the European Agri-food System and related up- and down-stream processes to mitigate emissions, 2018-2022) is a project that aims to

1. increase the understanding of C, N, P flows at farm and regional level,
2. contribute to closing nutrient cycles within cropland farming, from livestock to cropland farming and by reusing of waste/wastewater from food-industry,
3. assess the performance of agro-ecological systems and increase the sustainability of food production, and
4. contribute to improving the European Agricultural Policies in order to develop sustainable, resilient and inclusive economies that are part of circular and zero-waste societies.

NUTRI2CYCLE (Transition towards a more carbon and nutrient efficient agriculture in Europe, 2018-2022) is a collaboration originating from the EIP-Focus Group on Nutrient Recycling which aims to increase the C, N and P recycling rate and improve the overall sustainability and innovation capacity of European agricultural systems.

Looking at both agro-processing, animal husbandry and plant processing, the project will

1. benchmark mass flows of nutrients, organic carbon and GHG-footprint,
2. provide an assessment frame (toolbox) for evaluating potential impact of proposed innovations,
3. actively support concepts, techniques and scenarios put forward in EIP-Operational Groups,
4. optimize these scenarios using the toolbox,
5. showcase the most promising developments via prototypes and demos, in order to achieve a better nutrient stewardship across the value chain.

Using resilience thinking, the project SURE-Farm (Towards SUstainable and REsilient EU FARMing systems, 2017-2021) develops a comprehensive resilience enabling framework (Meuwissen et al., 2019), creates and applies resilience assessment tools and co-creates implementation roadmaps.

Its objectives are to measure the determinants of resilience; improve farmers' risk-related decisions and management; assess farm demographic changes as linked to labour markets; evaluate the current policy framework and develop resilience enhancing policy options. Finally, the project will make integrated long-term projections of farming system resilience and identify pathways to implement a resilience enhancing environment.

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