CLIMASOMA | Final report

Climate change adaptation through soil and crop management: Synthesis and ways forward

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The European Joint Programme (EJP) SOIL is a European network of research institutes in the field of soil science and science and agricultural soil management and policies. The consortium consists of 26 partner institutes from 24 countries.

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Climate change adaptation through soil and crop management: Synthesis and ways forward

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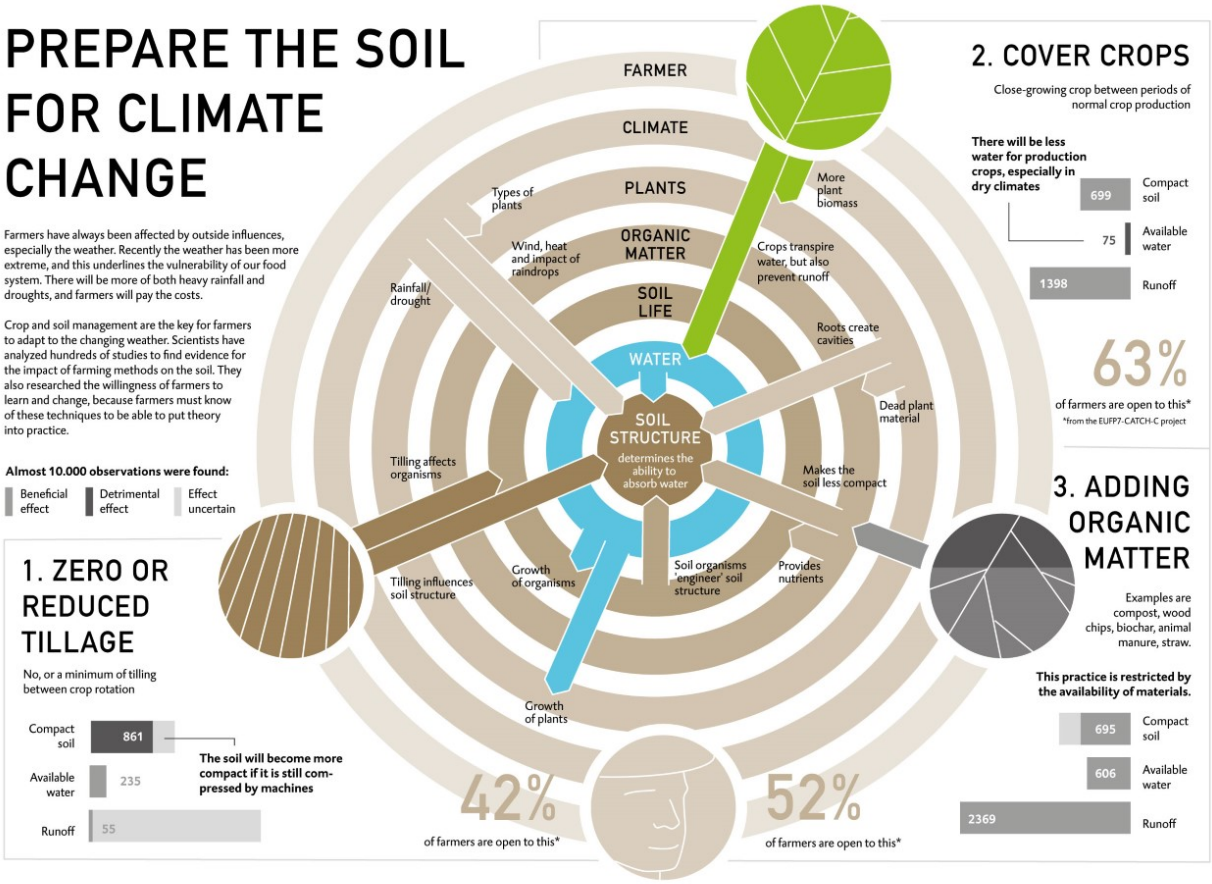
Summary



PREPARE THE SOIL FOR CLIMATE CHANGE

Farmers have always been affected by outside influences, especially the weather. Recently the weather has been more extreme, and this underlines the vulnerability of our food system. There will be more of both heavy rainfall and droughts, and farmers will pay the costs.

Crop and soil management are the key for farmers to adapt to the changing weather. Scientists have analyzed hundreds of studies to find evidence for the impact of farming methods on the soil. They also researched the willingness of farmers to learn and change, because farmers must know of these techniques to be able to put theory into practice.

Soil management and cropping systems enhancing soil structure are key to support the sustainable adaptation of EU agriculture to climate change. The occurrence of extreme weather events, such as drought in summer and floods in winter, will increase almost everywhere in the EU. Guidance on management practices and co-learning opportunities to help farmers adapt to these situations are necessary. Many practices exist and have already been subject to scientific research for several decades. Nevertheless, it is not always clear which practices have really proven effective in which contexts, what trade-offs have to be taken into account and which synergies might occur.

ClimaSoMa investigated the **implications of agricultural management practices for soil hydrological functioning under European agro-environmental conditions**. We synthesized the results of 36 selected meta-analyses (representing data from 2803 unique studies) studying the impact of soil and crop management practices on soil hydrological functioning. As such, we identified the effectiveness of the selected practices, and also remaining knowledge gaps. Important trade-offs and synergies related to crop production, water quality, and greenhouse gas emissions were also assessed based on the results of additional published meta-analyses. The results of this second order meta-analysis are described in Chapter 2, Soil and crop management for climate-smart soils.

In parallel, we identified and summarized the **socio-economic & political barriers experienced by farmers and incentives for the application of soil and crop management in climate adaptation strategies**. We present the results of a stock-take of EU policies and their instruments impacting agricultural management in Chapter 3, EU policy instruments driving soil management in view of climate adaptation . Barriers & drivers at the farm level in relation to improving soil health and climate change adaptation are discussed in Chapter 4, Farmer engagement as key to successful climate adaptation . The work includes perceptions of barriers and drivers that co-determine the willingness of farmers to act and adapt to climate change.

Human-induced climate change is expected to continue altering climate drivers (e.g., air temperature and precipitation) and enhancing CO_2 concentration in the atmosphere, also in the near-future. Changes in these conditions will alter soil processes and affect soil physical (e.g., water availability), chemical (e.g., SOM) and biological (e.g., microbial community and enzyme activity) functioning. It is therefore not only important to understand how our own actions and practices affect soil functioning, but also what is the direct impact of the changing climate. Chapter 5, Untangling the effect of climatic drivers with space-for-time or manipulation experiments provides a **perspective on how individual and combined effects of climate drivers (decreased and/or increased temperature and precipitation) and enhanced CO_2 concentration affect soil functioning** as well as the responses of soil to such changes. This chapter also discusses the limitations of different types of experimental approaches or research methodologies on the topic.

Saturated and near-saturated soil hydraulic conductivities K_h (mm.h^{-1}) determine the partitioning of precipitation into surface runoff and infiltration. They are fundamental to soils' susceptibility to preferential flow and indicate soil aeration properties. So-called pedotransfer functions are needed to estimate K_h from predictor variables, but they have been largely unsuccessful. We therefore analyzed bigger database, aiming at finding better predictors. In Chapter 6 Quantitative meta-analysis, publication bias and machine-learning to derive context-specific relationships, we collated OTIM-DB (Open Tension-disk Infiltrometer Meta-database), which builds on a meta-database published by *Jarvis, N., Koestel, J., Messing, I., Moeys, J., and Lindahl, A.: Influence of soil, land use and climatic factors on the hydraulic conductivity of soil, Hydrol. Earth Syst. Sci., 17, 5185–5195, 2013*.

The ability to extract, organize and synthesize knowledge from a huge body of literature is crucial to take into account context-specific relationships and variability in space and time. As a first step, structured information from scientific publications needs to be extracted to build a meta-database, which then can be analyzed and recommendations can be given in dependence to the pedo-climatic context. Manually building such a database by going through all publications is very time-consuming. In Chapter 7, Natural language processing as a tool to explore the information in vast bodies of literature we explore the potential of natural language processing (NLP) to extract metadata from agronomic studies.

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Chapter 1

Introduction

The occurrence of extreme weather events, such as high temperatures, drought in summer and floods in winter, will increase almost everywhere in the EU and guidance on management practices to help farmers adapt to these situations is necessary. Soil management and cropping systems to enhance organic matter contents and life in soil have often been proposed as a key way to support the sustainable adaptation of EU agriculture to climate change (EEA Signals 2019-Land and Soil in Europe).

The ecosystem services a soil can deliver and therefore its potential as climate adaptation tool, depend profoundly on its structure (Powlson et al., 2011) . This structure, or the physical arrangement of the soil pore space, influences transport of water and nutrients, as well as life in soil (e.g. root growth, faunal and microbial activity). **Soil structure is constantly evolving, driven by changes in exogeneous factors and mediated by various biological and physical processes** (Figure 1.1) that span time scales ranging from seconds to centuries (Meurer et al., 2020a). Because of the diversity of structure-forming processes and agents, soil is structured across a wide range of scales. In addition, most long-term field trials measure surrogate variables (or proxies) for soil structure, such as infiltration rates or soil hydraulic properties (water retention, hydraulic conductivity at and near saturation).

Although there is a wealth of knowledge available on the individual processes driving soil structure, **the combined effects of our soil management practices and cropping systems and completely new climates on soil hydrological and biological functioning is still poorly understood**. We lack systematic knowledge of the **speed, magnitude and reversibility** of changes in soil structure. We also lack **quantitative tools** to predict these changes as the development of mechanistic soil-crop models that account for soil structure dynamics is still in its infancy (Vogel et al., 2018). As ultimately, crop growth depends on the combined effects of different climatic drivers, it is also important to assess the impact of precipitation, partial pressure of CO_2 in the air and temperature on the processes driving soil structure dynamics and uptake of water and nutrients by plants. This can be done using the results of manipulated environment experiments (Rineau et al., 2019).

CLIMASOMA contributes to a **long-term alignment of research strategies connecting agricultural management, soil quality and climate adaptation potential** through its summary of the published literature and identification of knowledge gaps and research opportunities. The shared vision on this topic will result in clear additions to EJP Soil's roadmap for soil research.

The aim of this project was threefold:

1. To synthesize and quantify the **role of soil management on the hydrological soil functions** and the adaptive capacity and resilience of crop production to climate change.

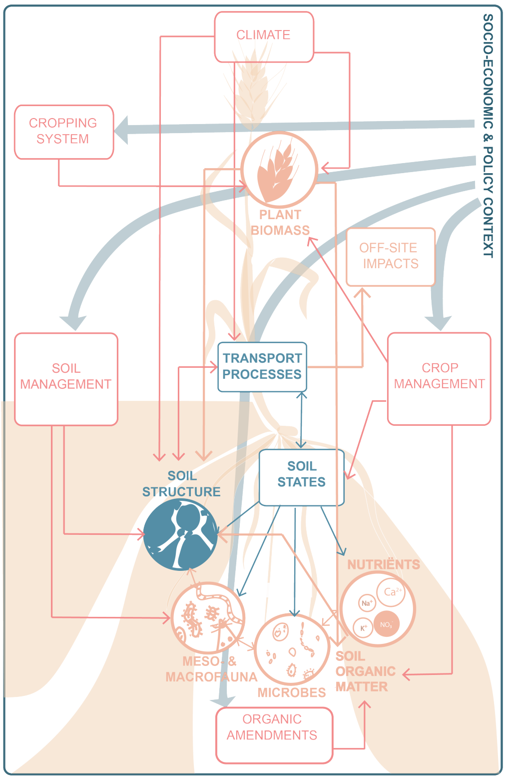

Figure 1.1: Scheme of drivers, agents and processes governing the dynamics of soil structure and its effects on the soil-plant-atmosphere system

2. To identify approaches using **soil structure dynamics and its driving processes in soil-crop modelling**.
3. To identify **future research needs** to deepen our understanding of the implementation and impact of soil management on soil hydrological and biological functioning to foster adaptation to climate change.

CLIMASOMA realized this by (i) collecting **relevant literature, databases and modelling approaches** covering bio-physical, agronomic and socio-economic & policy factors of climate change adaptation through their effect on soil structure as driver of hydrological and biological processes, (ii) structuring the data from existing work in an open **knowledge library** (https://www.bonares.de/knowledgelibrary/, “KLIB“) and an open new database on unsaturated hydraulic conductivity (OTIM) and (iii) analysing this knowledge library qualitatively and the database quantitatively to uncover **relationships and their interplay, causalities and knowledge gaps**. We also explored the potential of **text mining techniques** (natural language processing (NLP)) to gain more control over the vast amounts of literature available.

Chapter 2

Soil and crop management for climate-smart soils

2.1 Summary

Adopting soil and crop management practices that conserve or enhance soil structure is critical for supporting the sustainable adaptation of EU agriculture to climate change, as it should help maintain agricultural production in the face of increasing drought or water excess without impairing environmental quality. In this chapter, we evaluate the evidence for this assertion by synthesizing the results of 36 published meta-analyses of the effects of soil and crop management practices on soil physical and hydraulic properties and hydrological processes relevant for climate change adaptation in European agriculture. We also review an additional 127 meta-analyses that investigated synergies and trade-offs or help to explain effects of soil and crop management in terms of the underlying processes and mechanisms. We also identify, as far as possible, how responses to alternative soil-crop management systems vary under contrasting agro-environmental conditions (soil type, climates) across the EU. This information may help practitioners and policymakers to draw context-specific conclusions concerning the efficacy of management practices as climate adaptation tools.

Our synthesis demonstrates that organic soil amendments and the adoption of cropping systems and practices that maintain “continuous living cover” result in significant beneficial effects for the water regulation function of soils, mostly arising from the additional carbon inputs to soil and the stimulation of biological processes. These effects are clearly related to improved soil aggregation and enhanced bio-porosity, both of which reduce surface runoff and increase infiltration. One potentially negative consequence of systems that maintain “continuous living cover” is a reduction in soil water storage and groundwater recharge, which may be problematic in dry climates. No other significant trade-offs are known, while some important synergies have been identified including, for example, reductions in nitrate leaching to groundwater and greenhouse gas emissions for non-leguminous cover crop systems.

The benefits of reducing tillage intensity appear much less clear-cut. Increases in soil bulk density due to traffic compaction are commonly reported. However, biological activity under reduced and no-till practices is enhanced, which should in principle improve soil structure, increase infiltration capacity and reduce surface runoff and the losses of agro-chemicals to surface water. However, the evidence for these beneficial effects is not convincing and some significant trade-offs have also been identified, including yield penalties, increased herbicide use and leaching risks for pesticides and nitrate as well as larger greenhouse gas emissions.

2.2 Introduction

As a consequence of on-going climate change, the occurrence of extreme weather events, such as high temperatures, summer droughts, waterlogging and flooding, will most probably increase in many parts of Europe (IPCC (2021)) An urgent task is to develop guidance on management practices that help farmers adapt to these extreme weather situations.

The ecosystem services a soil can deliver, and therefore its potential as a climate adaptation tool, depend profoundly on its structure, which we define here as the physical arrangement of the soil pore space. Mediated by various biological (e.g. faunal and microbial activity) and physical processes (e.g. traffic compaction, wet-dry and freeze-thaw cycles), soil structure is constantly evolving at time scales ranging from seconds to centuries, driven by weather patterns as well as changes in climate and land management practices. In turn, soil structure strongly affects all life in soil as well as the abiotic hydrological processes that determine the balance between infiltration, surface runoff, drainage and the retention of water in soil and therefore the supply of water and nutrients to crop plants. Thus, adopting soil and crop management practices that enhance soil structure is a key way to support the sustainable adaptation of EU agriculture to climate change by maintaining agricultural production in the face of increasing drought or water excess, without impairing environmental quality. Some relevant management practices are considered part of conservation agriculture (Palm et al., 2014). Another more recently coined term is regenerative agriculture, which implicitly acknowledges past failures to preserve soil quality or soil health (Schreefel et al., 2020). Conservation agriculture to improve soil structure rests on three fundamental principles (Palm et al., 2014): i.) minimizing mechanical soil disturbance, ii.) maintaining soil cover by plants as much as possible and for as long as possible (i.e. aspects of both spatial and temporal coverage), and iii.) diversifying cropping. Another related term, which focuses specifically on climate adaptation, is "climate-smart agriculture", defined by FAO (2010) as "*. . . agriculture that sustainably increases productivity, enhances resilience, reduces greenhouse gases, and enhances achievement of national food security and development goals*".

The effects of soil and crop management practices on soil properties, soil hydrological and biological functioning and crop performance have been studied in many long-term field trials throughout the world. In addition to narrative reviews (e.g. Palm et al. (2014)), many quantitative meta-analyses synthesizing the findings of individual experiments have also been published. This is especially the case in the last few years (Beillouin et al., 2019a,c), probably because the number of field experiments that have been running for a sufficient length of time has only recently reached the critical mass required to enable these kinds of quantitative analysis. Indeed, the increase in the number of meta-analyses published on topics related to conservation agriculture has been so dramatic that three over-arching syntheses of these meta-analyses have also recently been published. Two of these studies focused on specific aspects of conservation agriculture, one on the use of organic amendments and cover crops on soil organic matter (SOM) storage (Bolinder et al., 2020))and another on the effects of crop diversification strategies on a range of ecosystem services (Beillouin et al., 2019a). In addition, Tamburini et al. (2020) carried out an even more ambitious and comprehensive global review of 98 meta-analyses of the effects of conservation agriculture on a wide range of ecosystem services, including a second-order meta-analysis on 69 of these studies. They concluded that diversification practices most often resulted in a 'win-win' situation for ecosystem services including crop yields, but that the often large variability in responses and the occurrence of trade-offs highlighted the need to analyze the context-dependency of outcomes, something which was only possible to do to a limited extent with such a broad-brush treatment. Furthermore, previous syntheses of meta-analyses on the benefits of conservation agriculture have placed very little emphasis (Tamburini et al., 2020) or none at all (Beillouin et al., 2019a; Bolinder et al., 2020; Beillouin et al., 2019b) on soil hydrological functioning even though this is key for climate change adaptation. In their synthesis, Tamburini et al. (2020) included 17 meta-analyses (involving 31 effects-size comparisons) relevant to water regulation, but most of these concerned water quality issues rather than hydrological functioning *per se*. Beillouin et al. (2019a) concluded that …“*our review reveals that a significant knowledge gap remains, in particular regarding water use*”.

In this study, we focus on the implications of agricultural management practices for soil hydrological functioning for climate change adaptation, specifically under European agro-environmental conditions. We do this by identifying and synthesizing existing meta-analyses of the response of soil physical/hydraulic properties and hydrological processes relevant for climate change adaptation to soil and crop management practices. Some meta-analyses focused only on the average effect of a given management practice and did not attempt to analyze variations in effects depending on local conditions such as soil type and climate. In those cases where such information is available, we summarize knowledge of context-specific effects of relevance for the range of agro-environmental conditions found within the EU, and as far as possible, explain these variations in terms of individual driving processes and mechanisms. This kind of information may explain local praxis in agricultural management (i.e. farmer choices) and will also enable practitioners and policymakers to draw context-specific conclusions concerning the efficacy of management practices as climate adaptation tools. We also perform analyses of redundancy and sensitivity and assess the quality of the documentation for the studies included in the synthesis. This qualitative evaluation highlights where consensus has been established and also identifies remaining knowledge gaps.

2.3 Materials and Methods

2.3.1 Literature search

A brainstorming exercise within the CLIMASOMA project consortium was first carried out to establish potential keywords to be used in the search string. This exercise consisted in mapping keywords on soil properties/states, processes, external drivers and human drivers related to soil water status, crop water supply and the resilience of agricultural ecosystems. This ensured a systematic approach for literature collection, which would be less biased by our personal previous knowledge and experience. A link to this map is given in the supplementary information. From this map, we developed the search string shown in Figure 2.1. This search string was used to search the published literature using Web of Knowledge in May 2021. This search returned 663 results. The approach is described and the results listed in the “query” notebook within the supplementary information.

All search results were manually assessed for their relevance to the objectives of our study. Meta-analyses that only included studies carried out outside Europe (i.e. North America or China) were not retained. Our search identified 36 relevant meta-analyses focusing on the effects of soil and crop management on soil physical properties and hydrological processes using effects ratios (Table S1 in the supplementary information, see Supplementary materials Chapter 1). Figure 2.2 shows the number of primary studies per publication year included in the 36 meta-analyses. A peak is clearly visible in 2014, which is explained by the fact that all of the selected meta-analyses were published after 2015. Our search string was also designed to identify meta-analyses of management effects on soil organic matter and biological response variables (e.g. microbial biomass), since these help to explain the observed effects on physical/hydraulic properties and hydrological responses, as well

soil AND meta-analysis NOT forest NOT urban AND

(management or tillage or cropping or crops or crop or (cover and crops) or (catch and crop) or residue or residues or fertilizer or manure or amendment or liming or compost or traffic or biochar or irrigation or intercropping or agroforestry) AND

hydraulic conductivity OR
water retention OR
available water OR
runoff OR
infiltration OR
bulk density OR
macroporosity OR
penetration resistance OR
soil strength OR
aggregate stability OR
aggregation OR
transpiration OR
(water and consumption) OR
yield OR
organic matter OR
organic carbon OR
(microbial OR faunal OR earthworm) AND (biomass OR activity)
root AND (depth or biomass or growth)

Figure 2.1: Search string used to identify relevant meta-analyses

as other studies that analyzed target variables representing potential “trade-offs” and synergies. With respect to the latter, we focused primarily on the impacts of management practices on crop yields, greenhouse gas emissions and water quality. An additional 154 published meta-analyses of this kind were identified by our literature search. These supporting studies are listed in the supplementary information (“*Supporting studies.xlsx*”).

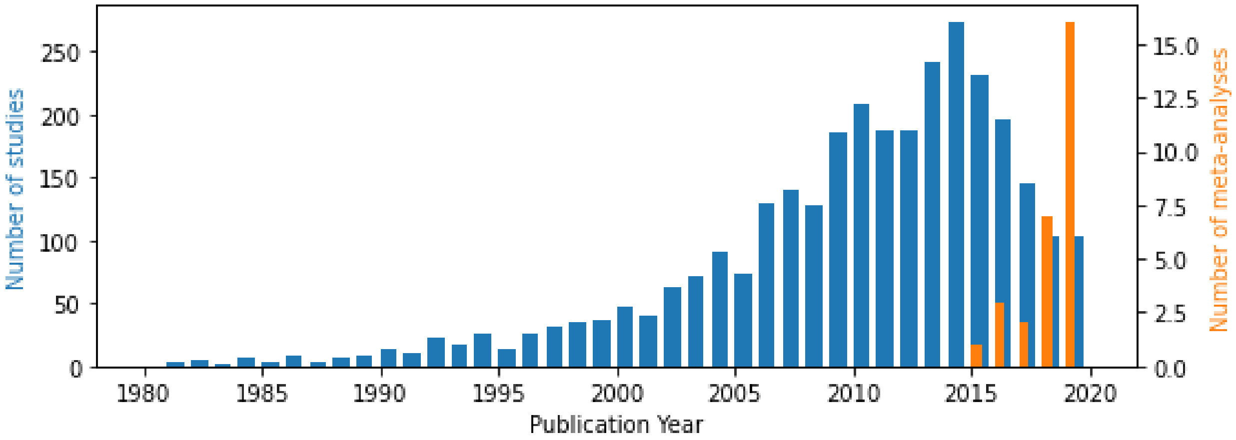

Figure 2.2: Number of primary studies included in the 36 selected meta-analyses published per year and the publication year of these meta-analyses.

The target variables (i.e. soil physical and hydraulic properties, soil water states) and drivers (i.e. soil/crop management practices) included in the 36 meta-analyses were then classified into a limited number of groups. The target variables were grouped into 5 classes: pore space properties (e.g. porosity, bulk density), hydraulic properties (e.g. saturated hydraulic conductivity, field capacity), mechanical properties (e.g. soil aggregate stability, penetration resistance), water flows (e.g. infiltration, surface runoff, drainage) and plant properties (e.g. root length density, water use efficiency). Similarly, the management practices were grouped into 5 classes: soil amendments (e.g. manure, biochar, organic farming systems), cropping practices and systems (e.g. cover crops, crop rotations), tillage systems (e.g. no-till), grazing management and irrigation. In total, we report 104 treatment comparisons from the 36 meta-analyses that summarize the impacts of drivers on response variables. The relationships (either positive, negative or neutral i.e. non-significant) between drivers and target variables were read from tables and figures in each meta-analysis. Figure 2.3 summarizes the statistical relationships found between the drivers and target variables in the selected meta-analyses.

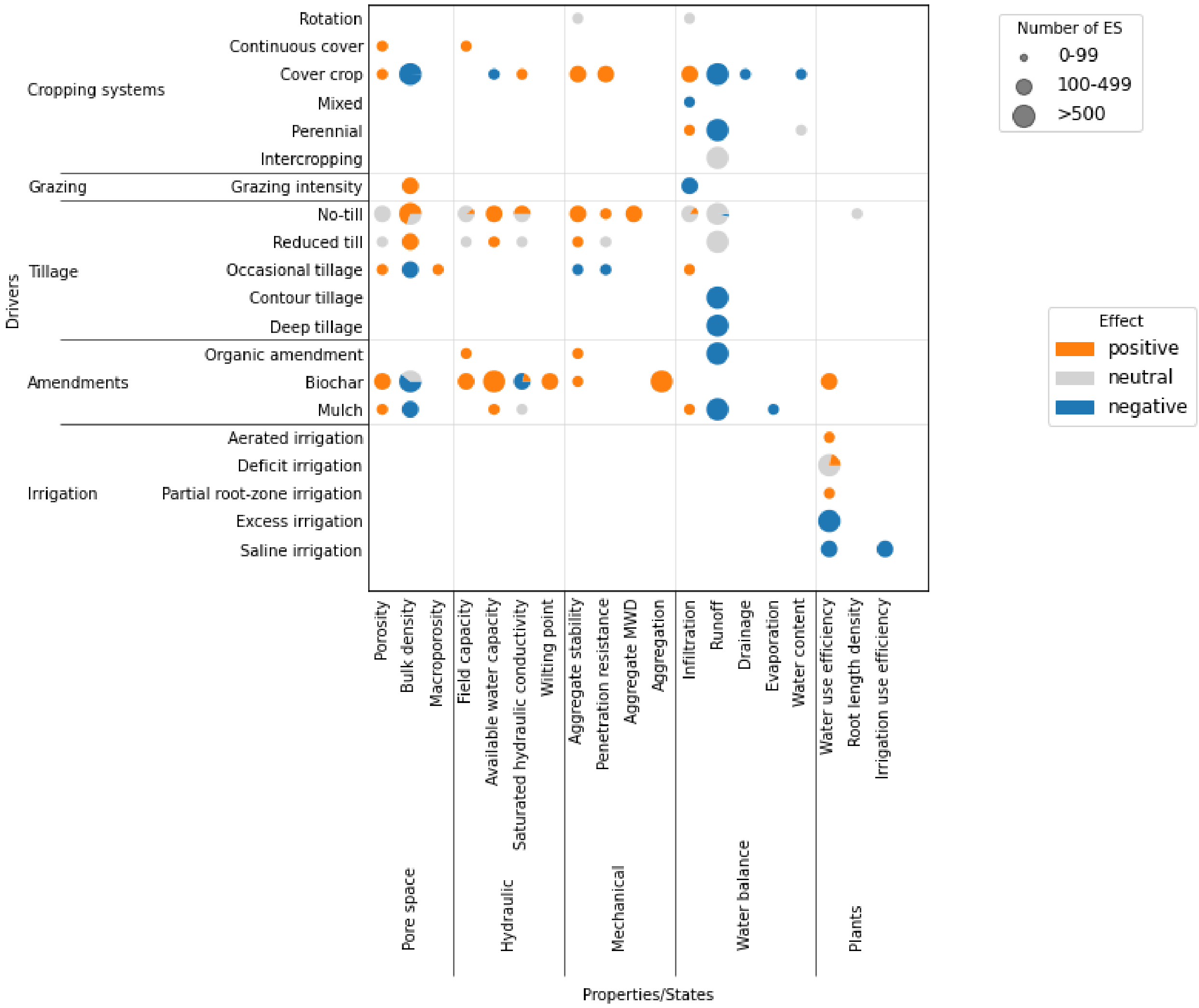

Figure 2.3: Effects of drivers (vertical axis) on target variables (horizontal axis) in the 36 selected meta-analyses. The coloured pie charts represent the directions of the statistical effects in the different meta-analyses, while the size of the circle indicates the total number of effects sizes (ES) reported. Blank cells denote that no data was available for this target variable in any of the selected meta-analyses.

Gaps in the scatter plots shown in Figure 2.3 indicate particular combinations of drivers and target variables that have not been the subject of meta-analysis according to our search criteria. Inspection of these figures suggests that there are several significant “knowledge gaps”. Although several meta-analyses have focused on the effects of irrigation management or organic amendments on water use efficiency, almost nothing has been published about the effects of soil management on root growth and water supply to crops, something which is critical for adaptation to future climates with more frequent and severe summer droughts. We can therefore only make inferences about the effects of soil management on crop transpiration from other terms in the soil water balance. Other knowledge gaps may be only apparent and therefore less serious: macroporosity is rarely studied in the context of meta-analysis, although infiltration has been much more frequently measured and these two variables should be strongly correlated. Figure 2.3 also indicates that some management practices have been less often the subject of field experiments including, for example, deep tillage, occasional tillage, and crop rotations. Presumably for reasons of cost, many long-term field experiments often only have simple designs, neglecting potentially interesting combinations of treatments, for example, no-till combined with the use of cover crops. Similarly, the interactions between soil and crop management and irrigation or drainage systems and practices do not appear to be a common topic of field experimentation.

Some additional potential knowledge gaps concerning the effects of soil management on water regulation functions are not revealed by inspection of Figure 2.3, since they concern variables that are rarely measured and so have not yet been the subject of meta-analysis. Most long-term field trials on the effects of soil and crop management practices on hydrological and biological functioning have measured surrogate variables (or proxies) for soil structure, such as infiltration rates or soil hydraulic properties (water retention, hydraulic conductivity at and near saturation). No meta-analyses have been performed yet for metrics quantifying different aspects of soil structure *per se* (Rabot et al., 2018) even though the application of X-ray imaging techniques to quantify soil structure is now becoming increasingly common. As a result, the number of X-ray studies published is rapidly increasing, so it should not be too long before it will be possible and worthwhile to carry out such an analysis.

2.3.2 Quality assessment

We performed a quality assessment of the selected 36 meta-analyses using 15 of the criteria proposed by (Beillouin et al., 2019b). Figure 2.4 presents a summary of the quality of the selected meta-analyses according to these criteria. The results for each individual meta-analysis are provided in Table S2 in the supplementary information. The Collaboration for Environmental Evidence (CEEDER) also provides criteria to assess the quality of meta-analysis (Konno et al. (2020); https://environmentalevidence.org/ceeder/). We attempted to use these criteria, but we felt that their complexity (four levels of quality) and the subjectivity of the decision-making made it difficult to assess some of the questions (e.g. 'Is the search comprehensive?' or 'Is the choice of synthesis approach appropriate?'). We therefore preferred to use the simpler yes/no approach of (Beillouin et al., 2019b).

Figure 2.4 shows that two of the quality criteria were not met by any of the 36 primary meta-analyses included in our study, in that no prior protocol was published and a list of excluded studies was not provided. Only a little over 40% of the meta-analyses included datasets in the paper, while only nine of the meta-analyses (i.e. 32%) investigated the important issue of publication bias (Philibert et al., 2012). The authors of these nine studies used simple statistical techniques such as frequency distributions of effects sizes or "funnel plots" of sample sizes against effect sizes to investigate whether experiments showing non-significant effects are under-represented in the literature. For both of these methods, symmetry of the distributions is taken to indicate a lack of bias. Only two of the nine studies detected any evidence of publication bias (Basche and DeLonge, 2019; Shackelford et al., 2019) and in both cases, the effects on the overall conclusions of the studies were thought

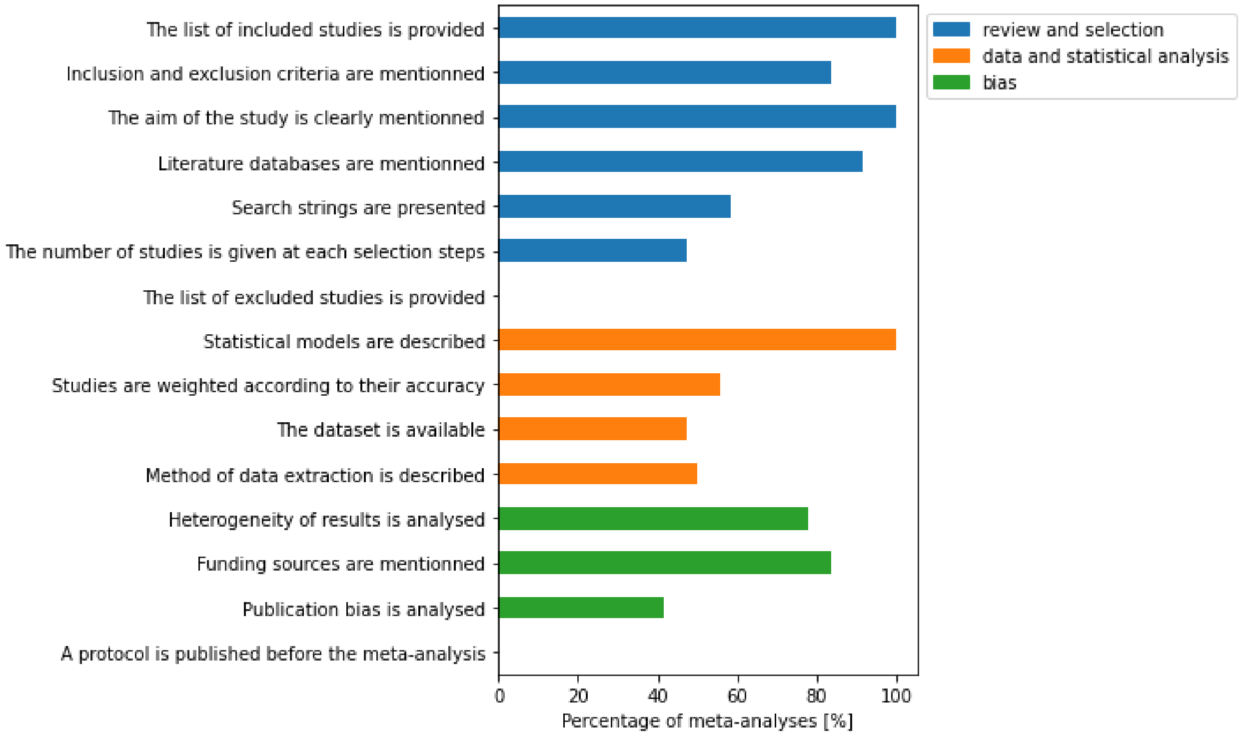

Figure 2.4: Proportion of the quality criteria defined by Bellouin et al. (2019a) that are met by the selected meta-analyses in this study.

to be marginal. Several studies also investigated sensitivity of the outcome to the exclusion of individual studies.

2.3.3 Redundancy

We performed a redundancy analysis to identify the proportion of common primary or source studies among the meta-analyses following the methodology of (Beillouin et al., 2019b). For each of the 36 selected meta-analyses, the references to the studies used were extracted from the supplementary materials. Each reference contained at least the name of the first author, the year of publication, the title, the journal and – if available – the DOI. Of the 3142 unique primary studies, 437 had no DOI. Old publications or publications not written in English were usually found to have no DOI. In some cases, the title and DOI were not available and we had to manually check these references based on contextual information supplied in the supplementary material. For instance, considering the string ‘Mgwango et al. 2011’ in a meta-analysis on tillage and knowing the study took place in ‘Tanzania’ led to a unique reference identification. In most cases, however, the title was provided in the meta-analysis and the DOI could be extracted automatically from the Cross-Ref database. We then manually checked if the title of the paper matched the one found on Cross-ref, to confirm the DOI assignment. Figure 2.5 shows the redundancy matrix between meta-analyses.

The notebook redundancy contains the results of this redundancy analysis. Note that for this analysis, the studies of Li et al. (2019) and Li et al. (2020a) were considered as one, as they both rely on the same database, but analyze different variables. First, we identified the studies shared between multiple meta-analyses and computed the percentage of shared studies per meta-analysis. Figure 2.6 shows the percentage of shared studies (number of shared studies divided by number

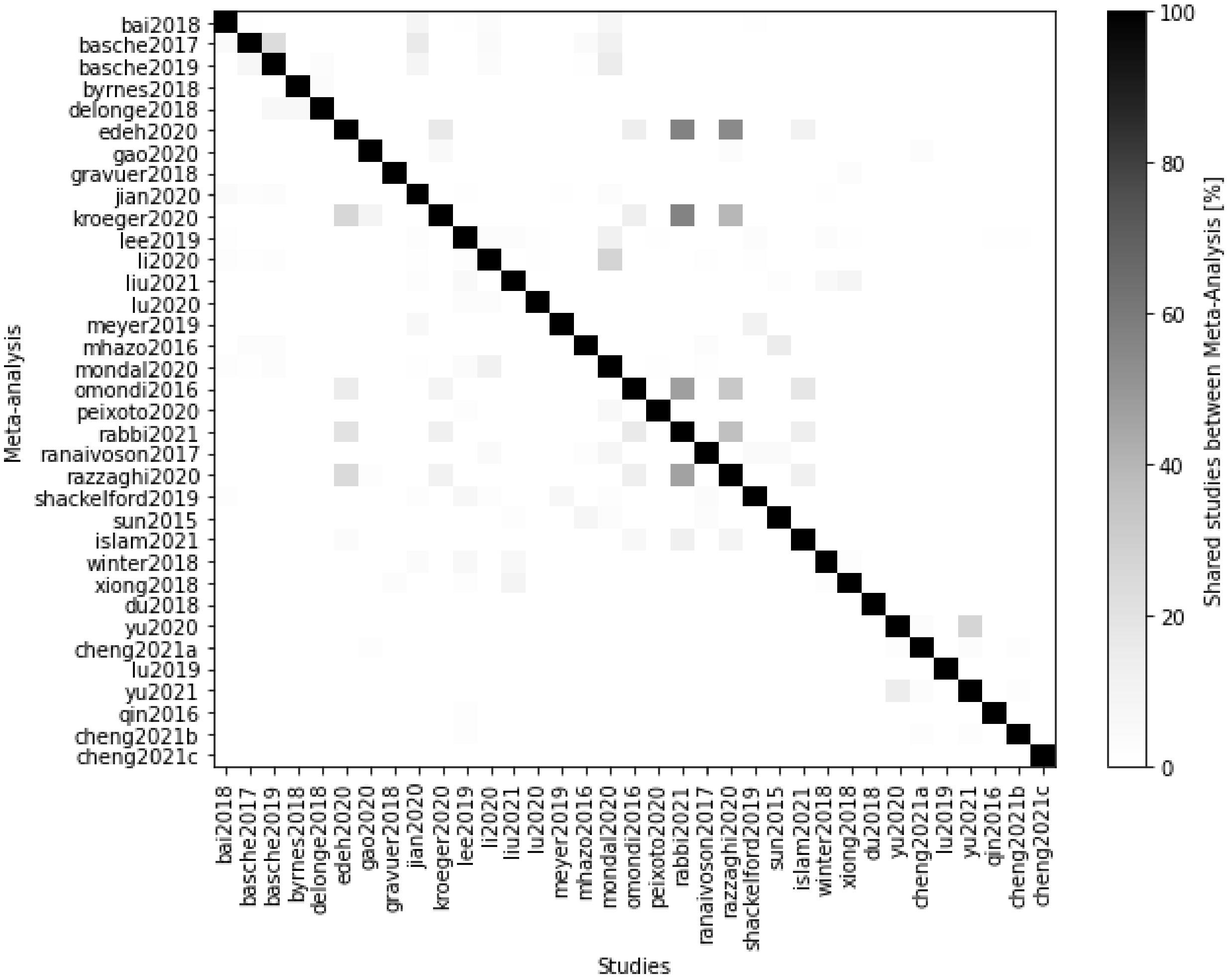

Figure 2.5: Redundancy matrix showing the percentage of shared studies among meta-analyses. The percentage refers to the number of shared studies divided by the total number of studies in the meta-analysis in the row. Note that this matrix is not symmetrical,because the percentage is computed for the meta-analysis in the row. If we had shown the number of shared studies as a number and not a percentage, this matrix would have been symmetrical.

of studies in the meta-analysis in the row times 100). Figure 2.6 shows for each meta-analysis the number of source studies that it shares with at least one other meta-analysis. Some meta-analyses share nearly 100% of their studies with another meta-analysis (e.g. Omondi et al. (2016) , Edeh et al. (2020)). In addition to the extent of redundancy, Figure 2.6 also shows the number of primary studies included in each meta-analysis. For example, Jian et al. (2020), Li et al. (2020a) and Mondal et al. (2020) considered more than 200 primary studies in their meta-analyses. Finally, Figure 2.7 shows for each meta-analysis the percentage of its primary studies that are shared with another meta-analysis. For example, the studies by Razzaghi et al. (2020) and Rabbi et al. (2021) share a large proportion of primary studies. Figure 2.6 also shows that nearly all of the primary studies included in these two meta-analyses are shared with another meta-analysis.

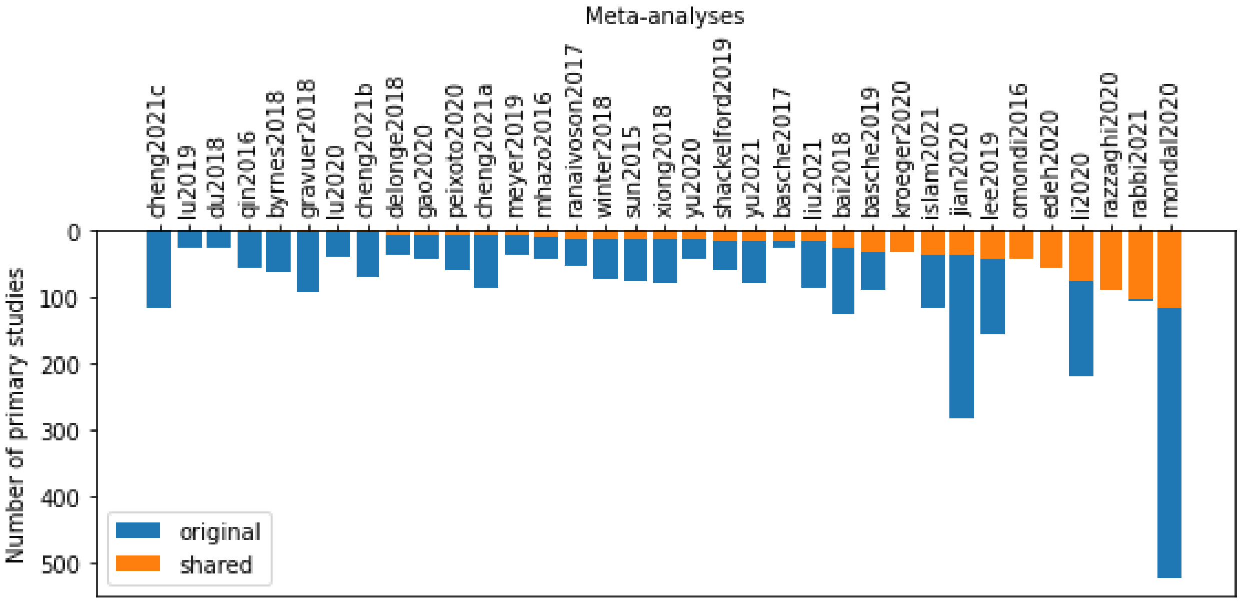

Figure 2.6: Histogram showing the number of studies per meta-analysis. The studies shared by at least one other meta-analysis are displayed in light green (shared), while the studies found only in this meta-analysis are shown in dark green (original).

2.4 Results and discussion

2.4.1 Cropping systems and practices

Broadly speaking, published meta-analyses that have investigated the effects of cropping systems and practices (Figure 2.3) fall into two categories: i.) studies analyzing the effects of maintaining a more continuous soil surface cover, either in a temporal (e.g. cover crops in arable rotations) or in a spatial sense (e.g. inter-row cover in widely-spaced row crops such as vineyards and orchards), and ii.) studies comparing farming systems (e.g. continuous arable contrasted with either perennial crops or rotations or mixed farming systems with livestock). In the following, we combine these two aspects, referring to both of them as cropping systems that as far as possible maintain a “continuous living cover” (Basche and DeLonge, 2017).

Figure 2.3 shows that meta-analyses have identified several beneficial effects of such agronomic practices on important physical and hydraulic properties in soil, such as porosity or bulk density,

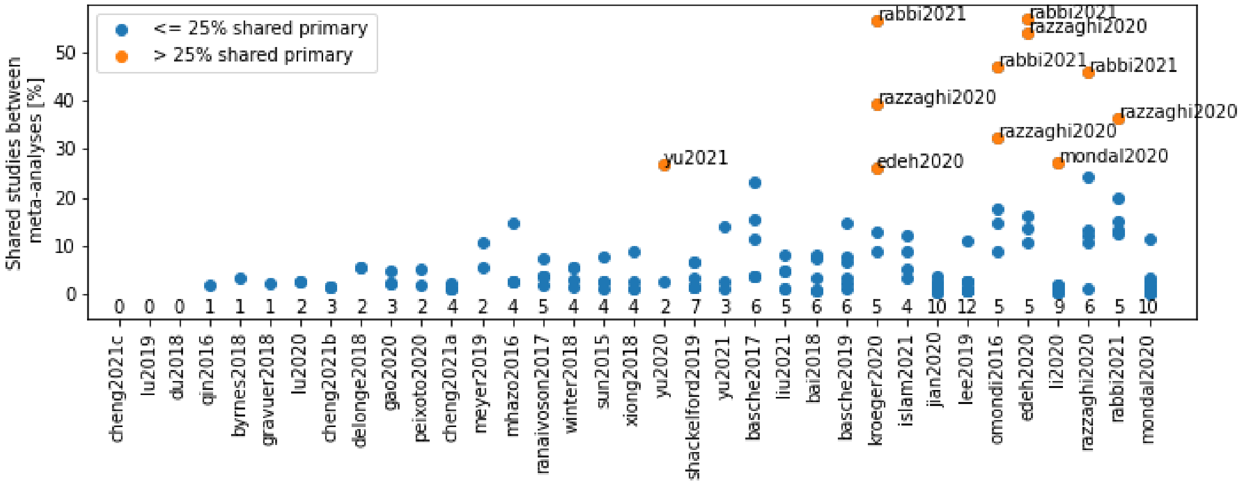

Figure 2.7: Redundancy among the selected meta-analyses (horizontal axis). Dots represent the percentage of shared primary studies between two meta-analyses. When this percentage is above 25%, the dots are shown in red and the name of the meta-analysis is displayed. For instance, Li et al. (2020a) shares more than 25% of its primary studies with the meta-analysis of Mondal et al. (2020). The number on the horizontal axis denotes the number of other meta-analyses that share primary studies with the meta-analysis named horizontally.Note that several meta-analysis do not share any studies with others. Meta-analysis are sorted according to the amount of shared primary studies they have (same order as Figure 2.6).

saturated hydraulic conductivity and aggregate stability (Basche and DeLonge, 2017; Jian et al., 2020). These positive effects are almost certainly due to a combination of the protective effects of surface cover against the degradation of soil structure by raindrop impact as well as the enhancement of various biological processes that occurs as a consequence of plant growth, root production and the additional carbon supply to the soil. In this respect, meta-analyses have demonstrated that practices that maintain a continuous living cover (e.g. rotations, cover crops) promote increases in microbial biomass, activity and diversity (Kim et al., 2020; Muhammad et al., 2021; Jian et al., 2020; Venter et al., 2016; Shackelford et al., 2019) and increase soil organic matter contents in the long-term (Poeplau and Don, 2015; King and Blesh, 2018; Bai et al., 2019; Bolinder et al., 2020; McClelland et al., 2021; Aguilera et al., 2013; Jian et al., 2020; McDaniel et al., 2014; Shackelford et al., 2019). This will both promote stable soil aggregation and reduce soil bulk density (Meurer et al., 2020a; Chenu et al., 2000; Meurer et al., 2020b). The abundance of soil meso- and macrofauna also increases under long-term cover cropping (Reeleder et al., 2006; Roarty et al., 2017) and perennial crops such as grass/clover leys (Fraser et al., 1994; Jarvis et al., 2017; Bertrand et al., 2015). Through their burrowing activity, these “ecosystem engineers” (Jones et al., 1994) create networks of large biopores in soil (Jarvis, 2007) that greatly increase saturated and near-saturated hydraulic conductivity and thus infiltration capacity (e.g. Bertrand et al. (2015); Capowiez et al. (2021)).

The changes in soil physical and hydraulic properties brought about by the introduction of continuous living cover have significant beneficial consequences for the water regulation function of soils. Thus, cover crops enhance infiltration capacity and reduce surface runoff (Liu et al., 2021; Basche and DeLonge, 2019; Lee et al., 2019; Jian et al., 2020; Xiong et al., 2018). An increased proportion of perennial crops in the rotation and the presence of ground cover between the rows of perennial crops (e.g. in vineyards) increase soil infiltration and reduce surface runoff (Liu et al., 2021; Basche and DeLonge, 2019; Xiong et al., 2018). These positive effects seem broadly similar regardless of climate (Liu et al., 2021; Xiong et al., 2018) .

Some negative consequences of mixed farming systems with grazing livestock for soil physical properties have been noted. Meta-analyses have shown that high grazing intensities result in significantly poorer soil physical quality, in terms of larger bulk densities (Byrnes et al., 2018) and reduced infiltration rates (Basche and DeLonge, 2019; DeLonge and Basche, 2018) as a result of compaction by animal trampling. These impacts of intensive grazing are similar irrespective of soil texture or climate, although they appear to be slightly larger in wetter climates (Byrnes et al., 2018; DeLonge and Basche, 2018). Another significant trade-off is that by increasing transpiration, systems employing "continuous living cover" may reduce soil water content (Shackelford et al., 2019) and decrease recharge to groundwater. Thus, for a combined dataset of 36 studies comprising both experimental and modelling studies, Meyer et al. (2019) found that cover crops reduced recharge by 27 mm/year on average with no apparent effects of climate, soil type or cropping system. For their meta-analysis based on a more limited dataset of six studies, Winter et al. (2018) found no significant effects of inter-row vegetation in vineyards on the soil water balance. Other impacts of cover crops on physical properties with adverse consequences for crop water supply have been reported, in particular an increase in soil penetration resistance and a reduced available water capacity (Jian et al., 2020), although it seems quite difficult to identify plausible mechanisms for such effects. As noted earlier, "continuous living cover" increases soil organic matter contents and both long-term field experiments and meta-analyses suggest that soil organic matter generally tends to increase the plant available water capacity. However, although the magnitude of this effect is still a matter of debate (Lal, 2020), in most cases it seems relatively small compared with the crop water demand (Minasny and McBratney, 2018b,a; Libohova et al., 2018) .

With respect to potential synergies and trade-offs, studies have shown that cover crops have either neutral or positive effects on main crop yields (Angus et al., 2015; Valkama et al., 2015; Tonitto et al., 2006; Quemada et al., 2013; Marcillo and Miguez, 2017), while non-leguminous cover crop species generally significantly reduce both nitrate leaching and N_20 emissions, although this is not the case for legumes (Muhammad et al., 2019; Valkama et al., 2015; Tonitto et al., 2006; Basche et al., 2014; Quemada et al., 2013; Shackelford et al., 2019). Our literature search did not reveal any meta-analyses on phosphorus or pesticide losses.

2.4.2 Tillage systems

A large number of meta-analyses have investigated the effects of tillage practices on soil properties and functions and the provision of various ecosystem services (see Figure 2.3). The control treatment in these published meta-analyses is usually conventional tillage (CT), which involves both inversion ploughing and shallow secondary tillage operations for seedbed preparation. This control treatment is then contrasted with either reduced (or minimum) tillage (RT), whereby the soil is no longer ploughed, or no-till (NT) systems in which the soil is left completely undisturbed, or both. One meta-analysis has investigated the effects of deep tillage and contour tillage on surface runoff (Xiong et al., 2018), while another has analyzed the effects of occasional tillage with no-till as the control treatment (Peixoto et al., 2020).

Reductions in the depth and intensity of tillage (i.e. from CT to RT to NT) strongly influence carbon cycling in soil-crop systems. Meta-analyses show that soil organic carbon concentrations increase under RT and NT systems in the uppermost soil layers (e.g. Bai et al. (2018); Lee et al. (2019)) and especially in fine-textured soils (Bai et al., 2019). The reasons for this are the lack of soil disturbance that promotes a stable aggregated structure, which affords a greater physical protection of C against microbial mineralization (Kan et al., 2021) as well as the elimination of physical mixing and re-distribution of C within the topsoil due to the absence of soil inversion by ploughing (Meurer et al., 2020d). Meta-analyses have shown that the accumulation of SOM universally found in surface soil layers under no-till, which reflects the deposition and accumulation of plant residues, is paralleled by a greater microbial biomass compared with CT (Li et al., 2020c; Lee et al., 2019; Chen et al., 2020; Li et al., 2018; Spurgeon et al., 2013; Li et al., 2020b; Zuber and Villamil, 2016). Similarly, enzyme activities are greater under NT (Lee et al., 2019; Zuber and Villamil, 2016). In their study, Zuber and Villamil found that NT systems increased β-glucosidase activity, but only close to the soil surface. Increases in enzyme activity under NT should indicate a greater functional microbial diversity. Indeed, meta-analyses have consistently found greater bacterial diversity under conservation tillage. In one early meta-analysis, a significantly larger diversity of fungal communities was also identified (Spurgeon et al., 2013), although later meta-analyses found no such effects (Graaff et al., 2019; Li et al., 2020b). Apparent contradictions may be explained by how crop residues are managed, as greater impacts on microbial diversity, including fungal communities, have been found in studies where NT treatments were combined with crop residue retention (Li et al., 2020c). We advocate that future studies should always report the combined practices of tillage and residue management, in order to gain further insights into the effects and interactions of tillage and agricultural residue management.

In addition to focusing on organic carbon concentrations in topsoil, differences in SOC stocks under conservation tillage systems in complete crop rooting zones and soil profiles are also of interest, not least from the point of view of climate change mitigation. From their meta-analysis of deeper soil profiles, Mangalassery et al. (2015) concluded that NT systems result in a net sequestration of carbon. This finding appears to contrast with Luo et al. (2010), who had earlier concluded that NT did not increase soil carbon stocks based on a meta-analysis of studies with measurements made to at least 40 cm depth. This is because although SOC is universally larger under NT than CT systems in the uppermost soil layers, it can be significantly smaller both at plough depth and in the upper subsoil (Angers and Eriksen-Hamel (2008)). Thus, for boreo-temperate climates, Haddaway et al. (2017) and Meurer et al. (2018) found increases in soil carbon stocks under NT compared to CT only in the topsoil, while no overall significant effect on carbon stocks was detected for soil profiles to 60 cm depth. In a more recent global meta-analysis, Mondal et al. (2020) found no significant differences in stocks of soil organic carbon between NT and CT systems while variations in response could not be attributed to either climate or soil type. In contrast, Sun et al. (2020) demonstrated significant effects of climate on the potential for carbon sequestration under NT systems. In their global analysis, they found that soil C sequestration was enhanced in warmer and drier regions, while soils under no-till in colder and wetter climates were as likely to lose soil C as gain C. These findings are supported by the regional-scale studies of Meurer et al. (2018) for boreo-temperate climates and González-Sánchez et al. (2012) and Aguilera et al. (2013) for Mediterranean climates, although for vineyards, Payen et al. (2021) found larger topsoil C sequestration in temperate climates than hot and dry climates. A loss of organic carbon following adoption of NT systems is due to a decrease in carbon input resulting from poorer crop growth (Pittelkow et al., 2015; Mangalassery et al., 2015), which compensates for reductions in carbon mineralization rates (Virto et al., 2012; Ogle et al., 2012). Such yield penalties under no-till are especially prevalent in colder and wetter climates (Sun et al., 2020).

Soil tillage directly affects soil macro-fauna by mechanically harming or killing them. In addition to these direct effects of soil disturbance, disruption of the soil also exposes soil macro-fauna to increased risks of desiccation and predation. Consequently, meta-analyses show that total earthworm biomass and abundance increase as tillage intensity is reduced (Bai et al., 2018; Spurgeon et al., 2013; Briones and Schmidt, 2017), with a negative relationship between tillage depth and earthworm abundance (Briones and Schmidt, 2017). Deep burrowing and surface-feeding (anecic) earthworm species are particularly favoured by NT systems, as their permanent burrows are no longer destroyed by ploughing and they have a better access to food resources. Thus, a lack of disturbance of the soil by tillage has also been shown to increase the diversity of earthworm populations in particular (Spurgeon et al., 2013; Briones and Schmidt, 2017; Chan, 2001) and soil fauna in general (Graaff et al., 2019).

Changes in tillage systems directly affect the physical properties of soil. For example, bulk density and penetration resistance often increase after the adoption of RT and NT systems (Lee et al., 2019; Li et al., 2020a, 2019) due to ongoing traffic compaction and the lack of loosening by cultivation (Hamza and Anderson, 2005). Peixoto et al. (2020) showed that these negative effects can be alleviated with occasional tillage. The impacts of conservation tillage practices on soil biological agents and processes also give rise to significant indirect effects on physical properties, hydrological processes and ecosystem services related to water regulation. Thus, meta-analyses have shown that saturated hydraulic conductivity and surface infiltration rates often, though not always, increase under conservation tillage compared with CT, especially for NT systems (Mondal et al., 2020; Basche and DeLonge, 2019; Li et al., 2020a, 2019). This suggests that the effects of the enhanced bioporosity in NT systems created by soil fauna, and especially anecic earthworms, on saturated and near-saturated hydraulic conductivity (Lee and Foster, 1991) generally outweigh the negative effects of increased bulk density. Thus, Spurgeon et al. (2013) showed in their meta-analysis that increased earthworm abundances and diversity found under NT systems were positively correlated with infiltration rates. Comparing ecological groups, they found that the density of anecic earthworms was positively associated with increased infiltration rates, whereas no effect was apparent for endogeic earthworms. Aggregate stability is also largest under NT systems, decreases when occasional tillage is practiced (Peixoto et al., 2020) and is smallest in CT systems (Bai et al., 2018). In their meta-analysis, Spurgeon et al. (2013) showed that improved aggregate stability under NT systems were positively associated with increases in fungal biomass. A lack of soil disturbance in NT systems also increases the mean size of aggregates produced in stability tests (Mondal et al., 2020; Li et al., 2020a). Several meta-analyses have demonstrated increases in field capacity and available water capacity under reduced and no-till systems (Mondal et al., 2020; Li et al., 2020a, 2019), presumably due to enhanced soil biological activity and increases in organic carbon content. This would improve water supply to crops under drought, although the effects appear relatively small.

In principle, better-developed soil macropore systems and improvements in aggregate stability should promote a more favourable water balance, with increases in infiltration and reductions in surface runoff. Figure 2.3 shows that the effect on runoff is one of the most studied hydrological processes related to tillage. The meta-analysis performed by Sun et al. (2020) found that reduced and no-till systems decreased surface runoff. However, these results do not appear to be conclusive as two later meta-analyses (Xiong et al., 2018; Mhazo et al., 2016) failed to detect significant effects of conservation tillage practices on surface runoff. However, Xiong et al. found that contour tillage and deep tillage both reduced surface runoff.

Adoption of no-till and reduced till systems involve several trade-offs, particularly concerning water quality, GHG emissions and crop yields. As noted earlier, NT systems tend to give smaller yields for many crops compared with conventional tillage (Pittelkow et al., 2015; Sun et al., 2020; Mangalassery et al., 2015). This may explain why no-till systems are still seldom adopted in Europe (Bai et al., 2018; Mangalassery et al., 2015), although reduced tillage (RT) is being increasingly adopted worldwide. In their comprehensive meta-analysis, Pittlekow et al. identified several reasons for variations in the yield response to no-till. Crop type was the most important, with no significant yield losses found under NT for oilseed, cotton and legume crops, while the yields of cereals and root crops were on average ca. 5% and 20% smaller respectively. In accordance with the results of the meta-analyses on stocks of soil organic carbon discussed earlier, Pittelkow et al. (2015) and Sun et al. (2020) also found climate to be a significant factor, with no significant yield losses for no-till systems under rain-fed conditions in dry climates. In contrast, Peixoto et al. (2020) showed that occasional tillage could increase crop yields in comparison with NT in dry regions and in soils with limited water retention capacity and availability, presumably by alleviating soil compaction and improved rooting.

With respect to water quality, Daryanto et al. (2017a) found on an overall 40% reduction in phosphorus loads in surface runoff for NT systems in comparison with CT. This was attributed to significant decreases in losses of particulate phosphorus, as concentrations of dissolved P actually increased in runoff under NT. For pesticides, Elias et al. (2018) found no significant differences in concentrations in surface runoff for 14 of the 18 compounds included in their meta-analysis. Pesticide concentrations were actually larger under NT for the remaining 4 compounds. For loads, no significant difference was detected in between CT and NT systems for 15 of the 18 pesticide compounds. For the three remaining pesticides, losses in surface runoff were larger under NT for metribuzin and dicamba and smaller for alachlor. As also noted by Elias et al., these results seem quite surprising given the documented effects of conservation tillage on soil structure and hydraulic properties in the uppermost soil layers discussed earlier, which should increase soil infiltration capacity and reduce surface runoff. For nitrate losses in surface runoff in conventional and no-till systems, Daryanto et al. (2017b) showed that a change to NT resulted in an increase of nitrate concentrations in surface runoff, but similar loads, implying that surface runoff was, as expected, less prevalent under NT.

Daryanto et al. (2017b) also performed a meta-analysis on nitrate leaching. They found larger leachate losses of nitrate under NT systems than CT, whereas the concentrations in leachate were similar under both tillage systems, indicating that the effect of NT on nitrate leaching was largely determined by increases in water percolation. No meta-analyses on the effects of tillage systems on pesticide leaching were uncovered by our literature search. Leaching is the outcome of several interacting processes involving many complex and poorly understood trade-offs (Alletto et al., 2010). In practice, with no mechanical disturbance, larger quantities of pesticides are often used to control weeds and diseases in NT systems. However, pesticide leaching will also be highly sensitive to changes induced by tillage in soil structure, microbial biomass and activity and SOC, since these will affect water flow velocities, degradation rates and the strength of adsorption in soil. Several field studies suggest that the better-preserved macropore networks established under RT and NT systems may enhance leaching by preferential flow (Jarvis, 2007; Alletto et al., 2010; Larsbo et al., 2009). Although it is difficult to draw firm conclusions about the effects of conservation tillage practices on pesticide leaching without the help of quantitative meta-analyses, we may tentatively conclude that the greater risk of macropore flow under RT and NT systems appears to outweigh any beneficial impacts of increases in SOC and microbial activity on pesticide adsorption and degradation.

Significant trade-offs have also been reported with respect to greenhouse gases. In an early meta-analysis, van Kessel et al. (2013) found no overall impact of reduced tillage or no-till on N_20 emissions, with observed increases in humid climates compensated by reductions in emissions in drier climates, although neither trend was significant. However, in a later meta-analysis, Mei et al. (2018) reported a significant overall increase of 18% in N_20 emissions under conservation tillage, with the largest effects in warmer and wetter climates and in finer-textured soils. In a recent meta-analysis, Shakoor et al. (2021) found significant increases of emissions of $C0_2$, N_20 and CH_4 of 7, 12 and 21% respectively under NT compared with CT. From the perspective of mitigating climate change, Guenet et al. (2021) concluded that increased emissions of greenhouse gases under no-till outweighed any minor gains in soil C storage.

2.4.3 Amendments

Biochar

Biochar is charcoal made for the purpose of soil amendment. It is a type of black carbon, resulting from incomplete combustion of organic matter through a process known as pyrolysis. Apart from its potential for long-term soil carbon sequestration, it also has beneficial effects on nutrient availability and soil physical properties (Joseph et al., 2021). Schmidt et al. (2021) reviewed 26 global meta-analyses published between 2016 and 2020 with a focus on the effects of biochar on agronomic performance. Some of the meta-analyses and some of the variables reported in our study were also included in their study. However, in our review we included a larger number of physical properties and two meta-analyses published in 2021.

We included seven meta-analyses on the effects of biochar on hydraulic properties in our review (Edeh et al., 2020; Omondi et al., 2016; Kroeger et al., 2021; Razzaghi et al., 2020; Gao et al., 2020; Rabbi et al., 2021; Islam et al., 2021). These analyses contain data from different soil types, textural classes and experimental conditions (i.e. field or laboratory/greenhouse study). Furthermore, biochars with different properties were applied at different rates. One of these studies (Kroeger et al., 2021) used multiple regression to evaluate the effects of these parameters while the others calculated mean effects for all data or data in sub-categories. Two of the seven meta-analyses only presented data in sub-categories (e.g. for different types of biochar) and did not present results for the overall effects of biochar addition. Nevertheless these analyses do show that biochar has several positive effects on soil hydraulic properties, but that these effects are dependent on all of the above-mentioned variables.

One out of four meta-analyses reported decreased bulk density after biochar addition and one reported no effect while the overall effect was not reported in the remaining studies (see Figure 2.3). Porosity increased in both meta-analyses where it was included. The density of biochar is low and the porosity is often high compared to soil, which may explain the observed effects. However, if biochar mainly fills existing pores, porosity will decrease and bulk density increase. Biochar will also influence these variables indirectly through its effects on aggregation (Pituello et al., 2018).

Four studies included effects of biochar addition on the water content at field capacity (θ_{fc}; pressure potentials in the range -0.033—0.01 MPa). Two of these studies reported a general increase in θ_{fc} while the overall effect was not reported for the other two. One of these three studies reported a general increase in the water content at permanent wilting point (θ_{pwp}; -1.5 MPa), while the overall effect was not presented in the other two. The plant available water content (θ_{paw}), defined as the difference between θ_{fc} and θ_{pwp}, increased in the two studies where overall effects were presented.

Pore sizes in biochars range over at least five orders of magnitude, from the sub-nanometer scale to pore diameters of the order of tens of micro-meters originating from partially preserved cellular structures (Brewer et al., 2014). However, a large fraction of the pore volume in biochar consists of pores in the nanometer size range (Downie et al., 2009). These pores will retain water at very low pressure potentials and therefore have the potential to increase θ_{pwp} upon biochar addition. It has been suggested that increases in θ_{paw} may be due to the filling of existing soil macropores with biochar which would shift the pore size distribution from large pores that drain quickly to pores that can retain water at field capacity (Liu et al., 2017). Biochar itself contains pores in the relevant size range (0.2—100 ţm in diameter) to contribute to θ_{paw}. Thus, inter-particle pores in biochar will also contribute to θ_{paw} depending on the size distribution and shapes of the biochar particles and their effects on soil aggregation (Burgeon et al., 2021). Since θ_{fc} is the sum of θ_{pwp} and θ_{paw}, the same processes are the likely causes of the observed increases in θ_{fc}.

The effects on water retention were in most cases larger for coarse-textured soils. Biochar with large microporosity can fill the larger inter-particle soil pores present in sandy soils so that the pore size distribution shifts towards smaller pores which can retain water at the pressure potentials corresponding to field capacity (Edeh et al., 2020; Omondi et al., 2016; Razzaghi et al., 2020; Rabbi et al., 2021). Moreover, fine-textured soil has a larger water retention capacity at θ_{fc} so that the relative changes induced by biochar may be smaller (Edeh et al., 2020). All seven meta-analyses included data on biochar production parameters (e.g. feedstock, pyrolysis temperature) and the chemical and physical properties of biochar. Generally, the influence of these parameters on the effects of biochar addition were minor with respect to soil water retention. Due to lack of data, the influence of the time between biochar application and measurements on the effects on water retention was not included. It is, however, clear from studies on century-old charcoal kiln sites that the properties of biochar and associated soil evolve over time (Cheng et al., 2008; Hardy et al., 2017).

One out of three meta-analyses showed an increase in saturated hydraulic conductivity following biochar addition, one showed a decrease, while the third study did not report overall effects. Saturated hydraulic conductivity is a function of the pore network properties, including connectivity of the macropores and pore bottle-necks (Koestel et al., 2018). A few studies have quantified the effects of biochar addition on the connectivity of macropore networks using X-ray tomography (e.g. Yu and Lu (2019); Yan et al. (2021)). These studies indicate that the connected macroporosity and the diameter of pore throats decrease in medium- to coarse-textured soils amended with biochar. However, the influence of soil texture on the effects of biochar on saturated hydraulic conductivity reported in the meta-analyses was not consistent.

Two meta-analyses reported measures of aggregate stability. Omondi et al. (2016) included only studies that reported mean weight diameter (MWD) using wet sieving, while Ul Islam et al., 2021 included studies that reported soil aggregate stability as a percentage of water-stable aggregates (WSA), as well as MWD or gravimetric mean diameter (GMD) using either wet sieving or dry sieving. Both studies showed that aggregate stability increased with biochar addition. The reason proposed for this effect was the influence of the added biochar on aggregation processes. The effects on aggregate stability increased with the time between biochar application and measurements (Islam et al., 2021) .

Only one meta-analysis focused on water use efficiency (Gao et al., 2020). They showed that both plant water use efficiency defined as the ratio of plant or fruit biomass to water supply, and leaf water use efficiency defined as the ratio of carbon dioxide uptake by leaves to the loss of water through transpiration, increased with biochar addition. Most biochars are alkaline and may increase soil pH, at least for acidic soils, which leads to improved conditions for plant growth. Biochars also contain nutrients that may become available for plant uptake. Indeed, previous studies have shown that the addition of biochar to nutrient poor acidic soils improves yields (Jeffery et al., 2017). Interestingly, in the meta-analysis of Gao et al. (2020), soil pH had different effects on plant and leaf water use efficiency. Leaf water use efficiency increased most for soils with pH less than 7, while plant water use efficiency increased most for soils with pH above 8. The reasons for these results could not be determined from their study. Medrano et al. (2015) showed that leaf water use efficiency may not be well correlated with plant water use efficiency. The large variability in reported effects (-36–313%) can be mainly attributed to differences in soil pH, biochar properties and amounts of added biochar.

The effects of the studied variables were in many cases larger for higher application rates. Often, laboratory studies used much larger application rates (>50 t ha^{-1}) than the field studies, probably for economic reasons. This may explain why effects usually were larger in laboratory or greenhouse experiments compared to field trials. Additionally, as pointed out by Rabbi et al. (2021), mixing of biochar after field applications is challenging and may be another reason why effects were sometimes small or insignificant for field experiments. The majority of the studies included in the meta-analyses were short-term experiments (i.e. duration <1 year). Future work should therefore focus on longer-term effects of biochar applications under realistic field conditions. This requires either long-term field experimentation, which is expensive, or the study of historic biochar sites. It is also impractical to study these effects for the almost infinite number of combinations of soils, biochars and climate that exists. The meta-analyses included in this study, which show large variations in effects for all the included variables, suggest that future work should also be directed towards finding biochars with specific properties (e.g. surface area, particle size) designed to improve soil physical properties under specific soil and climate conditions while maintaining or improving nutrient availability.

Other organic amendments, residue retention and mulching

Figure 2.3 shows that only a few meta-analyses have focused specifically on the effects of organic soil amendments or residue retention and mulching on soil properties relevant for water regulation functions. Instead these practices are often included in meta-analyses on conservation agriculture or tillage systems. In these studies, the effects of the treatments are combined. Furthermore, the influence of contrasting soils or climates have not been assessed.

Bai et al. (2018) studied the effects of different organic amendments applied in long-term field experiments on soil physical and hydraulic properties. They found that aggregate stability increased with organic amendments and that this effect was largest for compost. However, this beneficial effect decreased with time. Not surprisingly, Bai et al. (2018) also reported greater aggregate stability under organic farming systems compared with conventional agriculture. Xiong et al. (2018) also included soil amendments applied to agricultural land in their global meta-analysis on soil conservation practices. They found that application of soil amendments reduced both surface runoff and soil erosion. However, they provided no information on the type of amendments and how they were incorporated into soil. Gravuer et al. (2019) analysed effects of organic amendments (manure, biosolids and compost) applied to arid, semi-arid and Mediterranean rangelands. They found increased water contents at field capacity and reduced surface runoff. Additional benefits were increased soil organic carbon contents and above-ground net primary productivity, while trade-offs were increased CO_2 emissions, increased soil lead concentrations and increased losses of N and P in surface runoff.

Mulching means adding (or retaining) material on the soil surface without incorporation (Kader et al., 2017). In this review, we focus on organic mulches, but synthetic materials are also used. The most extreme example of mulching with artificial materials is plastic mulching, which has been shown to increase crop water efficiency under drought (Yu et al., 2021). The use of organic materials may have a number of beneficial effects on soil quality and the environment and it is, therefore, one important part of conservation agriculture. Mulching is typically carried out to limit soil evaporation, reduce soil runoff and erosion but it also affects, among other things, nutrient cycling, weed infestations and soil carbon storage (Ranaivoson et al., 2017). Mulching was included as one driver in four meta-analyses that studied effects on soil hydraulic functions. These meta-analyses showed positive effects on the rather limited number of hydraulic properties included. Three meta-analyses (one for agricultural land (Xiong et al., 2018), one for non-perennial crops (Ranaivoson et al., 2017) and one focusing only on tree crops (Liu et al., 2021) included effects of mulching on surface runoff. They all showed reduced surface runoff. The study for non-perennial crops also showed reduced soil evaporation and increased infiltration. These effects are already well-established in the scientific literature and in line with the intentions of mulching (Kader et al., 2017). The meta-analysis by Li et al. (2019) focused on effects of different tillage practices. Here we include the comparison between residue retention and no residue retention in no-till systems. Li et al. (2019) showed that residue retention led to a decrease in bulk density, an increase in total porosity and an increase in plant available water while it did not have significant effects on saturated hydraulic conductivity. They attributed this to increased accumulation of organic material on the soil surface, which leads to increased biological activity and soil aggregation.

2.4.4 Irrigation

Several recent meta-analyses have investigated the impacts of so-called deficit irrigation on water use efficiency and/or yields of a range of agricultural crops (Cheng et al., 2021c; Adu et al., 2018; Yu et al., 2020; Cheng et al., 2021b; Qin et al., 2016). The objective of this approach to irrigation scheduling is to reduce water use without significantly impacting yields by limiting the supply of water during periods of the growing season when it is less critical for crop growth. One of these meta-analyses (Cheng et al., 2021b) also synthesized the results of studies investigating the effects of partial root zone irrigation on water use efficiency and crop yields. This method also has the objective of saving water without impacting yields, but in this case by alternately supplying water to only one part of the root zone at each irrigation. These meta-analyses show that although these irrigation scheduling methods either have mostly neutral or sometimes positive effects on crop water use efficiency (see Figure 2.3), crop yields are significantly smaller compared to full irrigation for almost all crops and soil types. This implies that crop yields may in some cases be reduced less than water consumption, although these water savings may not compensate farmers for their yield losses. Another way to conserve high quality fresh water resources is to make use of brackish or saline water for irrigation. In their meta-analysis, Cheng et al. (2021a) showed how the decreases in water productivity, irrigation use efficiency and crop yields as a result of the use of salty irrigation water (see Figure 2.3) depends on crop type, irrigation methods, climates and soil type.

Based on the results of a meta-analysis, Qin et al. (2016) suggested that eliminating over-optimal (excess) irrigation by more efficient irrigation scheduling would improve the water use efficiency of citrus by 30% and yields by 20%. Du et al. (2018) showed that so-called aerated irrigation increases water use efficiency and yields of cereals and vegetables by ca. 20%, presumably by eliminating the development of anoxic conditions following irrigation.

2.5 Simulation models

Meta-analyses based on data from long-term field experiments have enabled us to identify some broad overall impacts of soil and crop management practices on water regulation and other related soil properties and processes. Ideally, we would like to achieve a more holistic and mechanistic understanding of these effects to support the development of climate change adaptation strategies by enabling predictions of rates of change and future impacts of changes in climate, land use and management. Soil-crop simulation models are potentially powerful tools in this respect (Stöckle and Kemanian, 2020; Robertson et al., 2015; Nendel et al., 2018; Jones et al., 2017) because they can “add value” to long-term field experiments. For example, soil-crop models can be used to identify plausible explanations of the observed treatment effects by filling in gaps in the data with respect to variables that were not measured. Once calibrated and validated against field data, they can also be used predictively, to extrapolate in time (Constantin et al., 2012) and also in space (e.g. Hoffmann et al. (2016); Coucheney et al. (2018)) and to perform scenario analyses. Soil-crop models should prove especially useful as tools to evaluate the trade-offs and synergies associated with alternative management practices, particularly if they can be linked to economic analyses (e.g. Parvin et al. (2022)).

Most studies of this kind to date have focused on the effects of rather simple management adaptations to climate variability or climate change, such as changes in dates of crop planting and harvest (e.g. Elliott et al. (2018) ; Constantin et al. (2019)). In contrast, there are surprisingly few examples of the use of soil-crop models to evaluate the effects management practices on properties and processes relevant for climate change adaptation (e.g. Nendel et al. (2018)). However, in one recent example, Tribouillois et al. (2018) used the STICS model to assess the impacts of introducing cover crops on the water and greenhouse gas balance at five different sites in southern France in rain-fed and irrigated cropping systems in present and future climates (2007 – 2052). They concluded that cover crops could potentially reduce greenhouse gas emissions from French agriculture from 5% to 9% by increasing soil carbon sequestration. However, cover crops also reduced drainage by ca. 20 mm/year and thereby potentially also groundwater recharge. Similarly, Meyer et al. (2020) calibrated the STICS model (Brisson et al., 2003) against data from a field experiment and then used the model to demonstrate that cover crops reduced annual drainage by 20-60 mm compared to plots under bare soil and would significantly reduce soil water contents for the next cash crop by, on average 20-50 mm, and by up to 80 mm under dry spring conditions. Scenario simulations with the calibrated model showed that mechanical destruction of the cover crop in late autumn and retaining the residues as mulch, would represent a good compromise between the multiple ecosystem services the cover crop provides during the fallow period, whilst avoiding the negative impacts on soil water availability for the next cash crop. Finally, Launay et al. (2021) used the STICS model to assess the potential for cover cropping to enhance carbon storage in soil and reduce N_20 emissions in France. The modelling was used to quantify trade-offs with respect to crop yields and water consumption, with the latter increasing by 13%, which was projected to increase the irrigation demand by ca. 80%. In another example, Cresswell et al. (1992) simulated the effects of conventional and no-tillage systems and the presence of surface seals and plough pans on the generation of surface runoff with a hydrological model (SWIM). They concluded that substantial changes in the soil water balance required major alterations in soil structure such as the development of surface crusts or plough pans. The model simulations, which were based on field-measured hydraulic properties and thus purely predictive, also suggested that surface runoff would be greater from conventionally-tilled land under high intensity or prolonged rain, but that soil evaporation rates are larger from no-tilled soil.

Model predictions are inevitably associated with errors arising from uncertainties in both model parameter values and process descriptions (Wallach and Thorburn, 2017; Beven, 2006; Wallach et al., 2021; Tao et al., 2018). Soil-crop models require comprehensive input data to support model parameterization, calibration and validation. Unfortunately, experimental data is inevitably scarce in relation to the uncertainty in model parameters. In calibrating models in such cases, parameter errors may compensate for model deficiencies leading to non-unique solutions (‘equifinality’, Beven (2006)). In addition, most data sets are too short to properly reflect contrasting weather conditions, which would be fundamental to constrain model predictions in a future climate. Parameter uncertainty is not always considered in soil-crop model applications. For example, Seidel et al. (2018) reported that nearly half the respondents to a questionnaire only used “trial and error” calibration. In such cases, even though a model appears to match the field data satisfactorily, it may be doing so for the wrong reasons, which means that model predictions, for example for a future climate, could be seriously in error (Bellocchi et al., 2011; He et al., 2017; Kersebaum et al., 2007, 2015). Multi-model comparisons have shown that differing calibration strategies among model users increases the variation of results among models that arises from contrasting process descriptions even when they are calibrated on the same data (Wallach et al. (2021)). This suggests the need for systematic and agreed protocols for calibration and validation of models in space and time.

Thus, despite their great potential and increasingly widespread use, few sufficiently comprehensive and critical tests have been carried out, so the validation status of many commonly used soil-crop models is unclear. In their recent review of crop modelling, Silva and Giller (2020) suggested that too little effort has been focused on model testing and model improvements. Specifically with respect to soil hydrology, the situation is reasonably clear-cut, since many crop models employ out-of-date process descriptions that are known to be inadequate. Brilli et al. (2017) highlighted the fact that these deficiencies in current generation soil-crop models often result in poor soil water balance simulations. This is probably because most soil-crop models were originally developed by teams of crop scientists who focused primarily on the description of plant physiology and crop growth with little, if any, input from soil physicists. This has resulted in an imbalance in model process descriptions, in which the importance of accurate descriptions of soil hydrological processes has often been underestimated. Empirical (phenomenological) approaches are commonly used to describe crop growth. This is understandable because the underlying processes are extremely complex and are still not easily amenable to mechanistic descriptions (Boote et al., 2013; Wu et al., 2016). However, most soil-crop models also use empirical models to describe water flow and storage in the soil (e.g. tipping bucket or reservoir models; Brilli et al. (2017)) even though physics-based approaches based on Richard’s equation are not difficult to parameterize, they are applicable to a wider range of hydrological conditions (e.g. shallow groundwater) and they also perform better (e.g. Diekkrüger et al. (1995); Kröbel et al. (2010); Guest et al. (2017)).

Similarly, many widely used soil-crop models represent crop water uptake and transpiration with overly simplified empirical models, even though suitable physics-based models are now available (Lier et al., 2013, 2008; Javaux et al., 2013; Couvreur et al., 2012; Sulis et al., 2019). These two issues are to some extent linked, as physics-based approaches to water uptake by plant roots require information on soil hydraulic functions that are not needed in tipping bucket or reservoir models. Model benchmarking studies (Heinen, 2014; Santos et al., 2017; Willigen et al., 2012) and comparative model tests against field data (Cai et al., 2018b,a) have demonstrated the errors that can be introduced by inadequate empirical descriptions of water uptake by crop roots, particularly those that do not account for compensatory mechanisms (e.g. Jarvis (2011)). The simplest physics-based models contain no more parameters than empirical models and they are also easier to estimate since they have a stronger physical basis (Javaux et al., 2013; Willigen et al., 2012). Thus, in principle, the predictive use of these models should also be more robust than empirical models.

It is frequently observed that plant roots may bypass soil layers that are compacted or otherwise hard to penetrate by preferentially growing through larger soil macropores (e.g. Hatano et al. (1988); Stewart et al. (1999); White and Kirkegaard (2010); Gaiser et al. (2013); Kautz et al. (2013)). The amounts of water and nutrients extracted by roots whilst growing through macropores may be limited by poor contact with the surrounding soil (White and Kirkegaard (2010)). Nevertheless, the ability of plants to by-pass compacted or other otherwise strong soil layers enables them to exploit water and nutrients stored in deeper soil layers with more favourable physical conditions (Colombi et al. (2018)). Most soil-crop models do not recognize the control of root growth by soil structure and soil strength (Stöckle and Kemanian, 2020; Wang and Smith, 2004) and the few exceptions mostly do so in a quite simplistic way, by making use of bulk density as a proxy for soil strength

(Robertson et al., 2015; Maharjan et al., 2018). Better descriptions of root growth are therefore needed in soil-crop models to support simulations of the effects of soil management (e.g. tillage and traffic compaction) on the crop water supply. Novel approaches to modelling the effects of soil constraints on plant root growth have been developed in recent years, some of which could be exploited in more widely used soil-crop models. For example, Gaiser et al. (2013) proposed a macroscopic approach that takes into account the effects of soil macropores on root growth in the soil profile. More recently, Landl et al. (2017) developed a root architecture model that accounts for the effects of soil strength on the growth and elongation of plant root systems, and thus the ability of plant roots to exploit pathways of least resistance through the soil such as soil macropores. De Moraes et al (2018) coupled this root architecture model with functions relating root penetration to soil water status and soil strength as well as a soil hydrological model based on Richards' equation including a sink term for water uptake by plant roots. Model predictions were compared with field data for soybean in Brazil and scenario simulations were run to illustrate the effects of a compacted soil layer on root growth and crop water uptake patterns.

One fundamental limitation of many soil-crop models is that they lack explicit descriptions of important management practices in conservation agriculture (Brilli, et al., 2017). For example, with some exceptions (e.g. Dilla et al. (2018)), most soil-crop models cannot simulate spatially-distributed cropping systems such as inter-cropping or agro-forestry. Similarly, most models cannot explicitly simulate the dynamic effects of tillage loosening and traffic compaction (Brilli et al. (2017)) as they assume that soil hydraulic properties are constant. A few modelling studies have employed empirical descriptions of within-year variations of soil physical and hydraulic properties induced by tillage loosening and subsequent consolidation (e.g. Strudley et al. (2008); Maharjan et al. (2018)). However, no existing soil-crop model can simulate changes in soil physical and hydraulic properties over longer time-scales such as decades or centuries, driven by climate and soil and crop management and mediated by soil biological agents and processes. This is the case even though the individual processes driving soil structure dynamics are reasonably well understood (Meurer et al., 2020a,d; Young et al., 1998)and its importance for soil hydrological processes has long been recognized (e.g. Cresswell et al. (1992); Connolly (1998)). There may be several reasons for this. Firstly, the web of interacting processes governing structure dynamics (Figure 2.1) is complex and difficult to quantify. Secondly, changes of soil hydraulic properties over time are rarely monitored in field experiments at the required time-scales necessary for model calibration and testing, most probably because these properties have always been considered to be static. In this respect, long-term changes arising from land use and climate change may also be hard to distinguish and disentangle from the changes in soil properties due to short-term management effects and within-year variations in weather. Existing soil-crop models can be used to quantify the effects of soil management on soil structure and hydrological processes at any given moment of time by running scenario simulations with contrasting soil physical and hydraulic properties (e.g. Cresswell et al. (1992)). However, such an approach cannot give any insights into the relevant time-scales of change. This is an important limitation when using existing soil-crop models to assess the implications of conservation agriculture for soil hydrological functioning and climate change adaptation. Some progress has recently been made towards the development of dynamic modelling approaches. For example, (Meurer et al., 2020a,d) proposed a simple concept for a modelling framework to account for soil structure dynamics arising from biological processes and agents such as root growth, earthworm bioturbation and soil organic matter turnover. Once incorporated into existing soil-crop models, this approach would enable simulation of the effects of long-term variations in pore size distribution, porosity and hydraulic functions on water flow, storage, crop water uptake and growth. Another limitation of soil-crop models relevant to climate change adaptation is that some plant traits that are important for water regulation are treated as constants, whereas plants may adapt and acclimatize, with key traits responding plastically to changes in environmental conditions (e.g. Nicotra and Davidson (2010); Vincent et al. (2020); Jarvis et al. (2021)).

Multi-model ensembles have been proposed as a way to account for errors and uncertainties in model process descriptions. Such an approach may help to improve the reliability of model predictions compared with single model applications (e.g. Wallach et al. (2018)). However, ensemble modelling will not help if the consensus view is wrong. It should be more important to focus on replacing inadequate model descriptions by demonstrably better alternatives.

2.6 Conclusions

A large number of meta-analyses have been published in recent years on the impacts of soil and crop management practices on soil properties and processes and the various ecosystem services and functions delivered by soil. In this report, we have synthesized these analyses with respect to the water regulation functions that are relevant for climate change adaptation in Europe. This synthesis has revealed a considerable degree of consensus concerning the effects of soil and crop management practices, despite the fact that meta-analyses cannot easily account for differences in experimental conditions among individual source studies, not least because many primary studies do not report all details of the experimental treatments. This overview has also identified several important knowledge gaps, particularly related to the effects of soil management on crop root growth and transpiration. Thus, conclusions related to the impacts of management on the crop water supply are necessarily based on inferences derived from proxy variables such as available water capacity and infiltration capacity.

Meta-analyses have demonstrated that the use of organic amendments and the adoption of cropping systems and practices that maintain, as far as possible, “continuous living cover” both result in significant beneficial effects for the water regulation function of soils, arising from the additional carbon inputs to soil and the stimulation of biological processes. These effects are clearly related to improvements in soil structure, both in terms of stable aggregation at the micro-scale and enhanced bio-porosity, both of which reduce surface runoff and increase infiltration. Meta-analyses show that amendment of soils with biochar generally increases aggregate stability, reduces bulk density, increases porosity and improves the plant available water capacity, particularly for coarse-textured soils.

One potentially negative consequence of management practices that maintain “continuous living cover” is a reduction in soil water storage and groundwater recharge that, in most cases, will likely outweigh any increases in soil water storage capacity due to carbon sequestration. This may be problematic in dry climates, although there is no clear evidence to suggest that yields of the main crop are affected. With respect to environmental quality, no other significant trade-offs are known, while some important synergies have been identified, in particular reductions in nitrate leaching to groundwater and greenhouse gas emissions. It can be noted here that the meta-analyses reviewed here have not distinguished between types of cover crop systems with respect to timings of sowing and termination, even though this may strongly influence the subsequent main crop and the environment (Meyer et al., 2020).

The evidence from meta-analyses to support the idea that reductions in tillage intensity improve crop water supply is limited and contradictory. The effects of no-till on SOM stocks and thus the capacity of the soil to store plant-available water appear to be minimal. In contrast, the amelioration of soil structure that occurs under RT and NT practices may improve infiltration capacity and reduce surface runoff, despite the increases in bulk density that are commonly reported, although the evidence for this is contradictory. Some significant trade-offs with RT and NT systems have also been identified. For example, yield penalties incurred under NT and increased weed pressure and/or increased herbicide use and thus leaching risks, especially in wetter and colder climates, constitute a barrier to adoption by farmers. Furthermore, greenhouse gas emissions are generally larger under NT, while leaching losses to groundwater of both nitrate and pesticides may also increase. Although we might expect losses of agro-chemicals in surface runoff to generally decrease under RT and NT, thereby compensating for greater leaching losses, this does not always appear to be the case. Reduced tillage intensity in the temporal sense (i.e. “occasional” tillage) may help to ameliorate some of the negative effects of no-till systems, whilst retaining some of the advantages.

In combination with field experiments, and despite uncertainties concerning the descriptions of soil hydrological processes in some instances, soil-crop simulation models should have an important role to play in resolving remaining knowledge gaps and evaluating trade-offs and synergies with respect to the impacts of management practices. It should be important to focus more efforts on improving the hydrological components of soil-crop models and their capability to describe the effects of a wider range of soil and crop management practices.

Chapter 3

EU policy instruments driving soil management in view of climate adaptation

3.1 Summary

In the broad context of agricultural activities farmers' operate in a complex web of external factors/drivers (agro-environmental policy, agri-business sector, natural resources, market), site-specific and personal characteristics (farm size, soils, agro-eco zoning location, infrastructure, machinery, human resources, expertise), resources inputs and outputs (labor, capital, energy), all requiring decisions to be made at short range (e.g., land occupation and crop selection, how much to fertilize/irrigate where and when) and long range (e.g. cropping system design, conservation agriculture, rotation, organic farming).

Public policies play an important role in farmers' and other actors' decisions influencing sustainability of crop production. In fact, unlike many other sectors, agriculture is one in which direct public intervention remains the norm rather than the exception. This makes farming activity sensitive to changes in public policy. Farmers' decisions are heavily influenced by market support, direct payments, agri-environmental policy and environmental legislation (European Environment Agency, 2015). According to Mills et al. (2017), other factors are important in the influencing farmer environmental decision-making, e.g. the attitudes of farmers, as well as the cultural, social and economic pressure that a farmer experiences.

The work presented in this report was carried out as part of the EU-funded CLIMASOMA project, within the H2020 European Joint Programme EJP Soil and an electronic version of this report, supporting materials maintained here.

The overall aim of CLIMASOMA is to contribute to an alignment of research strategies connecting agricultural management, soil quality and climate adaptation potential through its summary of the literature, its meta-analysis and its identification of knowledge gaps.

The European Commission published a Thematic Strategy for Soil Protection in September 2006, including an impact assessment and proposal for a Soils Framework Directive (SFD).

> ”Soil is a resource of common interest to the Community, although mainly private owned, and failure to protect it will undermine sustainability and long term competitiveness in Europe. Moreover, soil degradation has strong impacts on other areas of common interest to the Community, such as water, human health, climate change, nature and biodiversity protection, and food safety.”

(Commission of the European Communities, 2006).

In addition to establishing a common framework to protect soil on the basis of the principles of preservation of soil functions, prevention of soil degradation, mitigation of its effects, restoration of degraded soils, interestingly, the SFD also included the requirement to "identify, describe and assess the impact of some sectoral policies on soil degradation processes with a view to protect soil functions" (Commission of the European Communities, 2006). Due to the opposition from several Member States, the Soil Framework Directive never entered into force, there is still no European-wide political concept for soil protection. The main soil protection policies are directly linked with the cross-compliance system, greening requirements and Rural development policy (actual CAP 2014-2022). Soil protection also appears in the new Common Agricultural Policy, and indirectly linked with other sectorial policies (e.g. such as the Water Framework Directive, the Sustainable Use of Pesticide Directive, etc.). This chapter presents an inventory describing relevant EU-level agricultural, rural and environmental policies and their specific instruments impacting sustainable soil management practices for climate change adaptation, derived from official published data (e.g. Directive, Regulation, Rural Development programmes, Public report, EU funded projects

The inventory is mainly focused on sustainable soil management practices as climate change adaptation tools, as defined in the stocktaking on the impact of Soil Management practices conducted as part of EJP SOIL T2.4.1 (Paz, 2021), broadly grouped into the following's categories:

1. Soil tillage and soil cover (e.g. No till, Reduction of soil compaction etc.)
2. Crop and cropping system (rotation, Associations/intercropping/multiple cropping/sequential crop etc.)
3. Soil nutrient management and crop protection (Use of organic fertilizers, Methods for efficient fertilization etc.)
4. Water Management (Drainage systems, irrigation scheduling etc.)

Furthermore, instruments not directly linked with sustainable soil management practices, such of those related to the disaster risk reduction and risk management are also considered.

Agriculture is highly vulnerable to the impacts of climate change; the farming sector needs to adapt to climate change. Soil management is one tool farmers have to respond (Adapt) to climate change. Public policies play an important role in farmers' decisions influencing sustainability of crop production. The potential solutions, that are relevant for the CLIMASOMA project, offered by policies at various governance levels for adapting to climate change, namely through programmes and by introducing adaptation measures at farm level, have been identified in the inventory.

3.2 Introduction

3.2.1 Background and context

In the broad context of agricultural activities farmers operate in a complex web of external factors/drivers (agro-environmental policy, agri-business sector, natural resources, market), site-specific and personal characteristics (farm size, soils, agro-eco zoning location, infrastructure, machinery, human resources, expertise), resources inputs and outputs (labor, capital, energy). Farmers make decisions at various time scales, ranging from the short range (e.g., land occupation and crop selection, how much to fertilize/irrigate where and when) to the long range (e.g. cropping system design, conservation agriculture, rotation, organic farming).

Public policies play an important role in farmers' decisions and those decisions influence the sustainability of crop production. In fact, unlike many other sectors, direct public intervention remains the norm in the agricultural sector rather than the exception (The current represents around one third of the total EU budget). This makes farming activity sensitive to changes in public policy. Farmers' decisions are heavily influenced by market support, direct payments, agri-environmental policy and environmental legislation.

In September 2006 the European Commission published a Thematic Strategy for Soil Protection, including an impact assessment and proposal for a Soils Framework Directive (SFD). The Commission stated at the time: "Soil is a resource of common interest to the Community, although mainly private owned, and failure to protect it will undermine sustainability and long-term competitiveness in Europe. Moreover, soil degradation has strong impacts on other areas of common interest to the Community, such as water, human health, climate change, nature and biodiversity protection, and food safety." (Commission of the European Communities, 2006). Due to the opposition from several Member States, the Soil Framework Directive never entered into force, there is still no European-wide political concept for soil protection. The main soil protection policies are directly linked with the cross-compliance system[1] , greening requirements and rural development policy (actual CAP 2014-2022). Soil protection also appears in the new Common Agricultural Policy, and indirectly on other sectorial policies such as the Water Framework Directive, the Sustainable Use of Pesticide Directive, etc.

This chapter presents an inventory describing relevant EU-level agricultural, rural and environmental policies and their specific instruments impacting sustainable soil management practices for climate change adaptation.

The information gathered in this work is the result of a review of the available literature on EU policy and policy instruments. Farmer interviews or stakeholder workshops were not included in the current methodology but would most probably help gain valuable insights in the impact of existing policy on farmer decision-making.

The inventory is mainly focused on sustainable soil management practices as climate change adaptation tools, as defined in the stocktaking on the impact of Soil Management practices conducted as part of EJP SOIL T2.4.1 (Paz, 2021). The partners provided information on practices applied in their country and the estimated impacts of these practices on soil challenges.

Table 3.3 shows a subset of the identified sustainable soil management practices related to its impact of adaptation to climate change (a complete list of management practices is given in Annex 1, Supplementary materials Chapter 2).

Adaptation to climate change was the main impact of sustainable soil management practices in the water management category where the most reported were: irrigation scheduling, efficient irrigation systems, improve water storage capacity, drainage and determination of water use efficiency.

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[1] Cross-compliance (see Annex I for details) is a mechanism that links elements of both pillars of the CAP to farmers' compliance with various basic standards, and good practice. Its mission is essentially to help agriculture to develop sustainably and link the CAP better to other EU policies, including in the area of the environment and climate.

Table 3.1: Sustainable soil management practices and soils challenges

	Soil challenges	%
4.1. Soil tillage and soil cover		
4.1.2.Direct seeding	• Avoid soil erosion • Enhance soil biodiversity	2.9
4.1.3. Reduced tillage	• Avoid soil erosion • Enhance soil biodiversity	2.9
4.1.6. Controlled traffic	• Avoid soil erosion • Improve soil structure • Enhance water storage capacity	5.8
4.1.7. Low pressure (in) tires	• Improve soil structure • Enhance water storage capacity	2.9
4.1.8. Reduction of soil compaction	• Improve soil structure • Enhance water storage capacity	2.9
4.2 Crop and cropping system		
4.2.1. Crop rotations	• Improve soil structure • Enhance water storage capacity • Maintain/increase SOC • Enhance soil nutrient use efficiency	14.49
4.2.4 grassland/pasture with legumes	• Enhance water storage capacity	4.35
4.2.6. Mulching	• Enhance water storage capacity • Enhance soil nutrient use efficiency	1.45
4.3. Soil nutrient management and crop protection		4.35
4.3.1. Use of organic fertilizers	• Enhance water storage capacity	
4.4. Water Management		
4.4.1. Water Use Efficiency	• Enhance water storage capacity	4.35
4.4.2. Efficient irrigation systems	• Enhance water storage capacity • Enhance soil nutrient use efficiency	14.49
4.4.3. Irrigation scheduling	• Enhance water storage capacity • Enhance soil nutrient use efficiency	17.39
4.4.4. Drainage		5.8
4.4.5. Monitoring of soil salinisation	• Avoid salinisation and alkalinisation	5.8
4.4.7. Improve water storage capacity	• Enhance water storage capacity • Enhance soil nutrient use efficiency	10.14

Also contributing to adaptation, were reported practices to reduce soil erosion, improve soil structure, improve the soil water retention (e.g. direct seeding/no till/reduced till, low pressure in tires, controlled traffic, crop rotation) or decrease surface temperature (mulching).

3.3 Identification and description of key policy instruments

Table 3.2 shows the most relevant agro-environmental policies in the EU and related instruments directly and indirectly impacting farming practices and management in relation to climate change adaptation. The table is derived from official, published data (e.g. Directives, Regulations, Rural Development programmes. Public reports, EU funded projects…).

Table 3.2: Synthesis of main EU Policies relevant on farming practices and management in relation to climate change adaptation

EU Policies	Main objectives/scope	Policy area	Policy category
Common Agriculture Policy (CAP) 2014-2022	CAP is a key EU policy in a strategic sector in terms of enhance agricultural competitiveness, improve its sustainability and achieve greater effectiveness. To accomplish those challenges the CAP is organised into two pillars: The CAP Pillar I targets two main objectives: 1) Improvement of farm competitiveness by enhancing market orientation, removing all existing restrictions to production through market intervention, and providing income support – through basic payments and coupled support, 2) provision of environmental public goods, through the "Greening payments". The CAP Pillar II (Rural Development Policy 2014-2020) aims to pursue six priorities: 1) knowledge transfer, innovation, 2) organization of agri-food chains 3) risk management 4) ecosystem protection 5) contrast to climate change and CO_2 reduction 6) social inclusion and development in rural areas.	Agriculture	Economic

Table 3.2 – *Continued from previous page*

EU Policies	**Main objectives/scope**	**Policy area**	**Policy category**
Common Agriculture Policy (CAP) 2023-2027	In 2018, the European Commission presented legislative proposals on the common agricultural policy beyond 2020. The post-2020 CAP reform set out 9 specific objectives to meet broad ongoing challenges related to the economic health of the farm sector, the environment and climate, and socio-economic development of EU's rural areas. The most important elements introduced in the proposal of the new CAP are represented by: • New policy instrument tool - The New Delivery Model, more flexibility for Member States in the implementation of the CAP – through National Strategic Plan, • Enhanced conditionality; 1) Greening moved from the direct payment to the conditionality (Rotation instead of crop diversification), 2) Introduction of new SMR (e.g. Water Framework Directive) and GAEC, 3) Introduction of the eco-scheme in Pillar 1 to maximize environmental and climate benefits for Agriculture Policy (CAP) 2023-2027	Agriculture	Economic
The European Green Deal COM(2019) 640 final (including the EU Adaptation to Climate Change, farm to fork and biodiversity strategies, and EU Soil Strategy for 2030)	The EU Green Deal provides a roadmap to make Europe the first climate-neutral continent by 2050. The Green Deal touches upon specific policy areas (Measures to cut pollution rapidly and efficiently, clean energy, sustainable industry, etc). The agricultural sector is asked to promote ways to ensure more sustainable food systems, through the farm to fork and biodiversity strategies.	Horizontal	Planning
Nitrate Directive (ND) - (Directive 91/676/EEC), and **Groundwater Directive (GWD)** (Directive 2006/118/EC)	The Nitrate Directive aims to protect water quality across Europe by preventing nitrate from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. The groundwater directive aims to protect groundwater against pollution and deterioration. This include procedures for assessing the chemical composition of groundwater and measures to reduce levels of pollutants.	Water	Regulation
Water Framework Directive (WFD) - (Directive 2000/60/EC)	The water framework directive aims to achieve a good qualitative and quantitative status of all water bodies in the EU. It intends to contribute to preserve, protect and improve environmental quality and the prudent and rational use of natural resources, introducing several new ecological, economic and social approaches and concepts in the EU water management (e.g. good ecological status, full cost recovery, public participation).	Water	Regulation
Sustainable Use of Pesticide Directive (PD) - (Directive 2009/128/CE)	The pesticide directive establishes a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides.	Chemicals	Regulation

Table 3.2 – *Continued from previous page*

EU Policies	**Main objectives/scope**	**Policy area**	**Policy category**
EU mission "Caring for soil is caring for life" within the research programme Horizon Europe	Targets by 2030: at least 75% of all soils in the EU are healthy for food, people, nature and climate. The proposed mission combines research and innovation, education and training, investments and the demonstration of good practices.	Horizontal	Planning
LIFE ("The Financial Instrument for the Environment")	Though soil has not been a core theme of the LIFE programme, many soil-related projects have been funded over the last 21 years, and the new LIFE Programme will increase the focus on soil. The LIFE climate sub-programme also promotes Integrated projects that implement EU policy and strategy on climate change adaptation.	Horizontal	Economic

Many of the identified regulatory policies use a mix of instruments, often including both mandatory and voluntary elements. The economic instruments are those sanctioning or incentivising behaviour through market mechanisms. The CAP's greening measures or payments, for example, are an attempt to incentivise agricultural practices that go above and beyond standards and regulations covered under Cross-compliance. In addition, funding available under the Regional Development Programmes compensates farmers for transaction costs related to the provision of in relation to providing public goods or ecosystem services. The economic instruments under the water framework directive aim to establish pricing systems reflecting real economic costs. The underlying idea is to motivate farmers to increase their water use efficiency and look for crops better adapted to the natural environment (McNeill et al., 2021).

Policy approach and related instruments are complex and often operate in a policy-mix, they can be broadly grouped into the following four categories.

3.4 Description of the most relevant agro-environmental policies

The description of each instrument includes, whenever possible with the information available, the following aspects:

- Name of the instrument
- Rationale and objectives: description of the instrument and its objectives
- Geographical coverage (e.g. EU, national, regional, local)
- Targeted actors: who is targeted by the instrument?

3.4.1 Common Agricultural Policies (CAP) - 2014-2022

Table 3.3: Policy approaches and Instruments

Policy approach	**Instruments**	**Mechanism**	**Example**
Mandatory Regulation	• Directives • Standard setting	Imposing obligations, prohibitions or restrictions.	Nitrate Directive, Water Framework Directive, Sustainable Use of Pesticide Directive CAP Cross compliance
Economic	• Pricing, such as tariffs, taxes • Subsidies • Incentives for Voluntary agreements	Make bad practices/inputs more expensive to adopt or rewarding positive behaviour • Make good practices cheaper to adopt • Help overcome large initial investments • Reduce transaction costs	CAP Pillar I subsidies Eco-scheme (CAP Pillar I) and Agri-environmental schemes (CAP Pillar II)
Planning	• Action programmes/ plans • Strategies	Orienting policy-making.	European Green Deal F2F and biodiversity strategies
Facilitating instruments (Education and information)	• Training programs • Extension services • R&D	Increasing technical capacity and know-how	Farm advisory services and cooperation under CAP Pillar II

Rationale and objectives

CAP is in place since 1962, and over time has undergone different reforms in order to face the challenges of the sector. These reforms have increased market orientation for agriculture while providing income support and safety net mechanisms for producers. They also improved the integration of environmental requirements and reinforced support for rural development across the EU. The new policy continues along this reform path, moving from product to producer support and now to a more land-based approach. This is in response to the challenges facing the sector, many of which are driven by factors that are external to agriculture. These have been identified as:

Economic: food security and globalisation, a declining rate of productivity growth, price volatility, pressures on production costs due to high input prices and the deteriorating position of farmers in the food supply chain,
Environmental: resource efficiency, soil and water quality and threats to habitats and biodiversity,
Territorial: where rural areas are faced with demographic, economic and social developments including depopulation and relocation of businesses.

Since the role of the CAP is to provide a policy framework that supports and encourages producers to address these challenges while remaining coherent with other EU policies, this translates into three long-term CAP objectives (European Commission, 2020b):

- viable food production
- sustainable management of natural resources and climate action
- balanced territorial development

To achieve these long-term goals, the existing CAP instruments had to be adapted. The CAP reform 2014-2020 therefore focused on the operational objectives of delivering more effective policy instruments, designed to improve the competitiveness of the agricultural sector and its sustainability/effectiveness on the long term Figure 3.1.

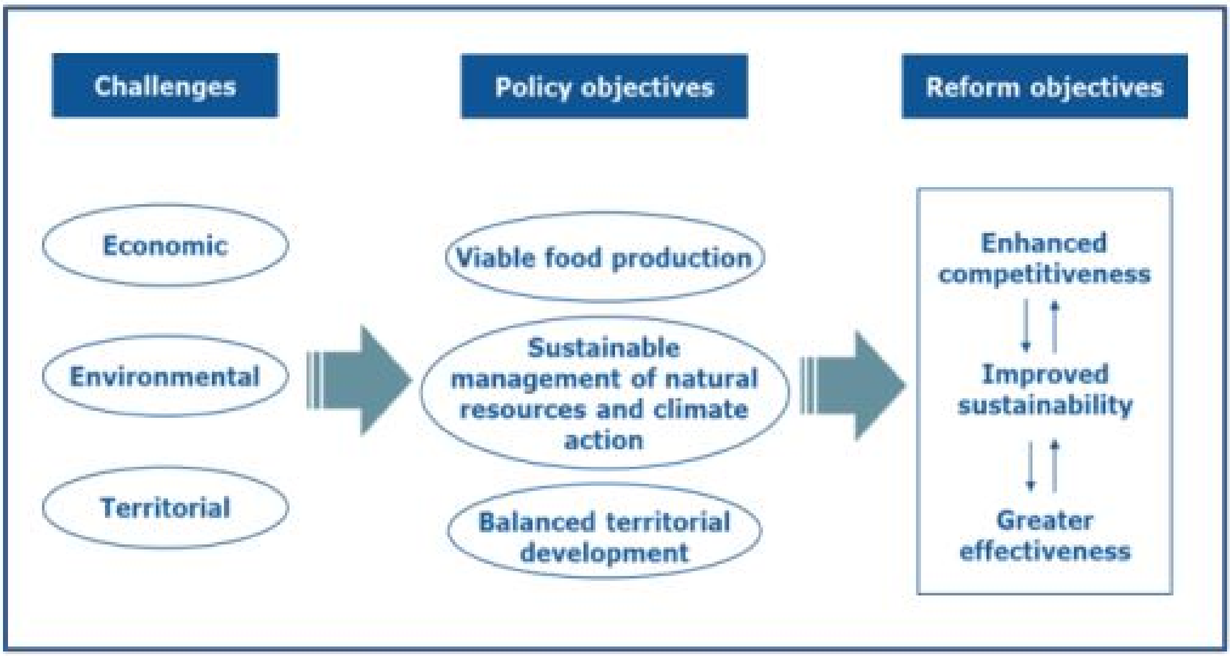


Figure 3.1: The objectives of the CAP 2014-2020. *Source: Agricultural Policy Perspectives Brief, No 5, European Commission, December 2013.*

To accomplish those objectives, the architecture of the CAP is organised into a legislative framework based on four regulations, with one – called horizontal (European Commission, 2013b)- dedicated to the financing, management, monitoring, and the cross-compliance rules of the CAP (Figure 3.2).

For the period 2014-2020, PAC funding is covered by two funds:

- EAGF - European Agricultural Guarantee Fund for the First Pillar, finances direct payments to farmers and agricultural market support measures
- EAFRD - European Agricultural Fund for Rural Development, co-finances national rural development programmes (RDPs).

First pillar: direct payments & market measures

Direct payments (European Commission, 2013a) to farmers aim to:

- provide basic income support through the basic payments and coupled support
- provide of environmental public goods, through the “Greening payments” (practices beneficial for the climate and the environment)

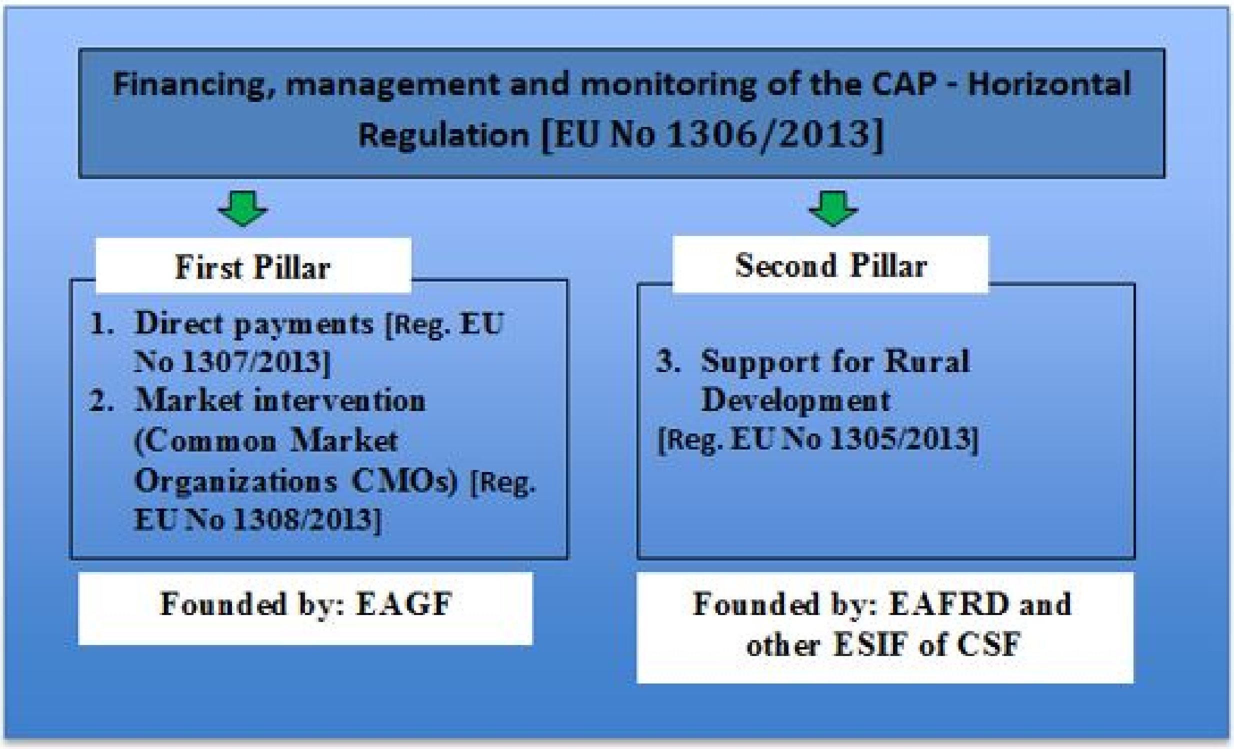


Figure 3.2: The architecture of the CAP 2014-2020

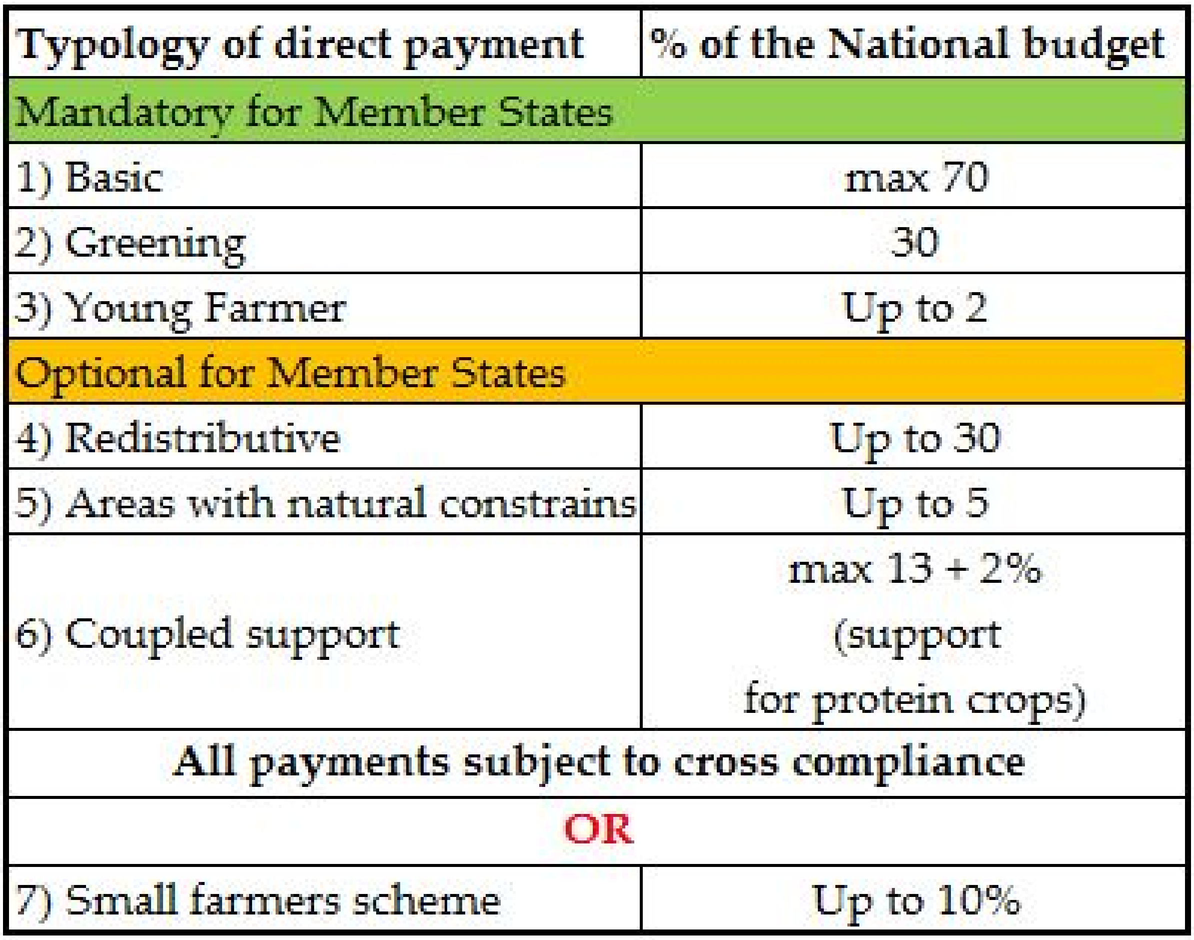
Market measures (European Commission, 2013a) are the rules that regulate agricultural markets in the EU, as well as the EU support to specific sectors, the promotion of EU agricultural products (through marketing standards, geographical indications, labels, etc.), the market instruments (private storage, intervention) and the support to a more balanced food supply chain. International trade measures such as licences and tariffs, as well as competition rules, also come under this banner.

The changes in the direct payment scheme are amongst the most important changes introduced with the CAP 2014-2020 (together with the introduction of the greening component). In fact, the single payment scheme has been split into 7 typologies, by giving to the Member States a large flexibility in its definition, expect for the greening with a fixed 30% of the national amount of money allocated for direct payments to each member state from the European Union budget (European Commission, 2020a).

Greening payment structure

Farmers can obtain greening payments (Figure 3.3) when they implement (depending on the farming typology and size) one or more of the following practices:

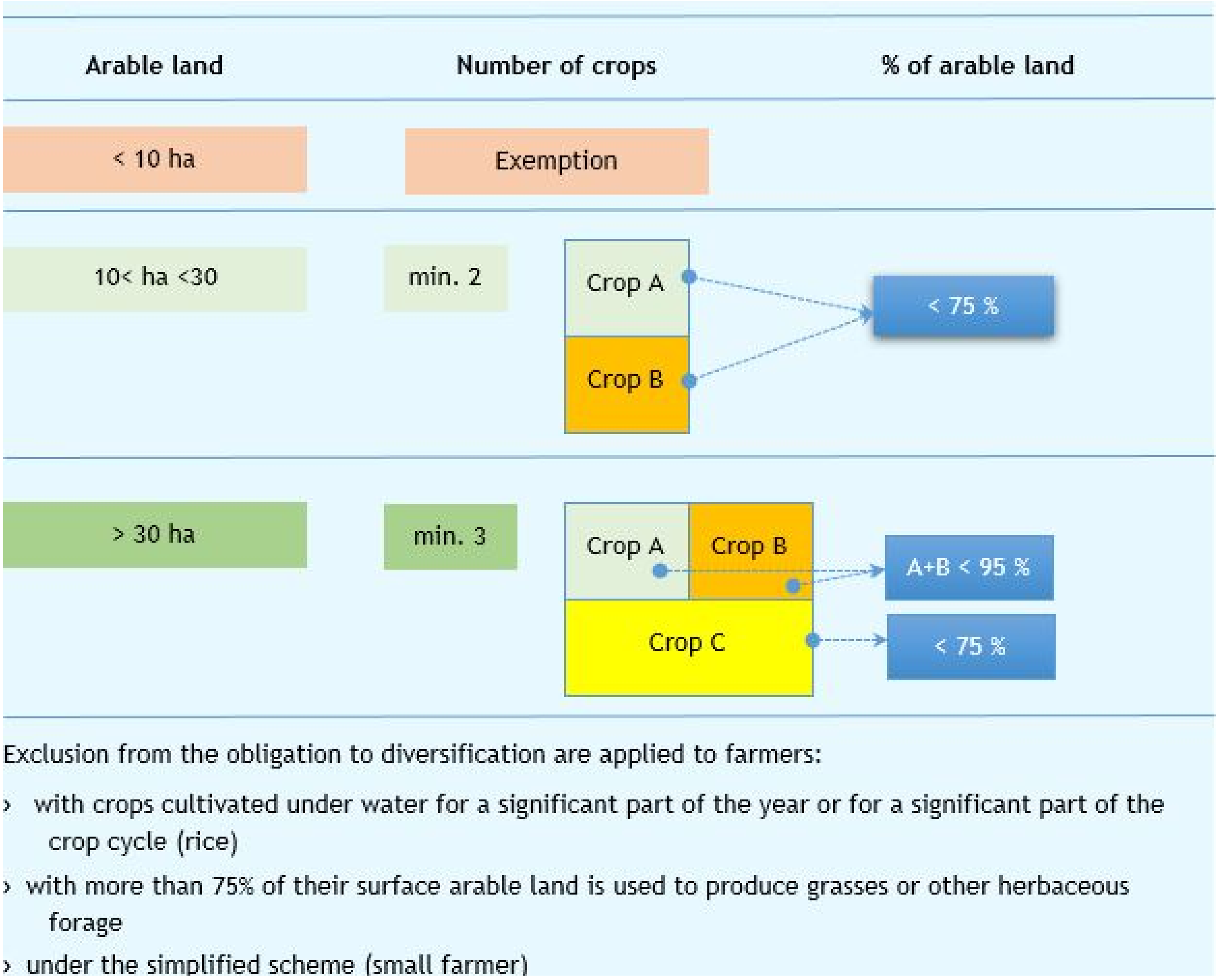
1. crop diversification only applies to arable crops, while permanent crops (orchards, olive groves, vineyards, pastures) are exempted
2. maintaining existing permanent grassland
3. dedicating 5% of arable land to Ecological Focus Area (EFA), where the arable land of a



Typology of direct payment	% of the National budget
Mandatory for Member States	
1) Basic	max 70
2) Greening	30
3) Young Farmer	Up to 2
Optional for Member States	
4) Redistributive	Up to 30
5) Areas with natural constrains	Up to 5
6) Coupled support	max 13 + 2% (support for protein crops)
All payments subject to cross compliance	
OR	
7) Small farmers scheme	Up to 10%

holding covers more than 15 hectares, with a view to safeguarding and improving biodiversity on farms

These three practices are set by the community regulation and are the same for all farmers in the European Union, without the possibility for the Member States to change their constraints.



Exclusion from the obligation to diversification are applied to farmers:

- with crops cultivated under water for a significant part of the year or for a significant part of the crop cycle (rice)
- with more than 75% of their surface arable land is used to produce grasses or other herbaceous forage
- under the simplified scheme (small farmer)

Figure 3.3: Greening payment structure

The purpose of the requirement for ecological focus areas on arable land is to safeguard and improve biodiversity on farms. Art. 93 of REG. (EU) No 1307/2013 establishes a list of features and areas that consist of:

- areas directly impacting biodiversity, such as land lying fallow, terraces, landscape features, buffer strips, strips along forest edges, afforested areas and agro-forestry areas; or
- areas indirectly impacting biodiversity through a reduced use of inputs on the farm, such as areas covered with short rotation coppice, catch crops and winter green cover, and nitrogen-fixing crops.

Second pillar: rural development

Rural development (European Commission, 2013c) funds invest in local projects to support the socio-economic fabric of rural areas. Rural development funds can for example support the setting up of an artisan's business, invest in sustainable irrigation systems, organise trainings for farmers, help develop agri-tourism, etc. Rural development also plays a central role for climate-related actions by supporting farm modernisation to cut energy consumption, produce renewable energy, improve input efficiency and reduce emissions.

Rural Development Policy is part of the overall programming of EU territorial/cohesion policies, defined by the Common Strategic Framework (CSF). All European Structural and Investment Funds (ESI Found, Regulation (EU) No 1303/2013) should contribute to the Europe 2020 strategy for smart (*developing an economy based on knowledge and innovation*), sustainable (*promoting a more resource efficient, greener and more competitive economy*) and inclusive (*fostering a high employment economy which delivers on social and territorial cohesion*) growth, in synergies between them.

The six priorities, reported in Figure 1, of rural development are articulated in 18 aspects, or "Focus areas" (Fa - see annex III, Supplementary materials Chapter 2 for details). The Focus areas represent one of the main new features of the new 2014-2020 rural development programming cycle. They arise from the observation that the intervention measures envisaged by the rural development plans normally contribute to more than one strategic objective.

The link to agricultural practices that improve soil quality is potentially substantial because two focus areas specifically target soil:

Focus area 4C preventing soil erosion and improving soil management
Focus area 5E fostering carbon conservation and sequestration in agriculture

Table 3.4: Measures of RDPs that have potential impacts on agricultural practices and/or climate change adaptation

Art.	Measure	Sub measure	Beneficiaries	Maximum amount (EUR) or rate	Potential impacts on agricultural practices and/or climate change adaption
14	M1) Knowledge transfer and information actions	M1.1 - Support for vocational training and skills acquisition M1.2 - Demonstration activities and information actions M1.3. - Support for short-term farm and forest management exchanges as well as farm and forest visits	Provider(s) of formal training and actions (which are not part of regular education programmes or curricula) Provider(s) of demonstration activities and information actions Provider(s) of exchanges and visits	The EU Rural Development Regulation does not set specific limits to funding allocations under M1.	Measure can potentially support vocational training, demonstration activities, information provision necessary to promote agricultural management for SICS through exchanges and visits
15	M2) Advisory services, farm management and farm relief services	M2.1 - Support to help benefit from the use of advisory services M2.2 - Support for the setting up of farm management, farm relief and farm advisory services M.2.3- Support for training of advisors	Providers of advice The authority or body selected to set up farm management, farm relief farm advisory or forest advisory services Entities providing the advisor training	For each Advice (voucher) 1,500 Up to 200,000 for 3 years for consultant training	Measure funds part of the cost of the CAP farm advisory system which Member States must provide (see Section 3.5). Could support advisory services on management of soils to improve soil quality, improve the economic and environmental performance and climate friendliness and resilience.
17	M4) Investments in physical assets	M4.1 - Support to improve the overall performance and sustainability of an agricultural holding	Farmers or groups of farmers	40% of eligible costs (50% in less developed regions). In some cases (young farmer, organic agriculture commitment) an additional 20% can be applied.	A large spectrum of investments can be founded under this measure depending on the choose of MS/regions: purchase of new agricultural machinery and equipment conservation tillage equipment, irrigation systems, drainage system, investment in precision agriculture technology to improve soil management practice.

Table 3.4 – *Continued from previous page*

Art.	**Measure**	**Sub measure**	**Beneficiaries**	**Maximum amount (EUR) or rate**	**Potential impacts on agricultural practices and/or climate change adaption**
18	M5) restoring agricultural production potential damaged by natural disasters and introduction of appropriate prevention	M 5.1) support for investments in preventive actions aimed at reducing the consequences of probable natural disasters, adverse climatic events and catastrophic events M5.2) Support for investments for the restoration of agricultural land and production potential damaged by natural disasters, adverse climatic events and catastrophic events	Groups of farmers	100% Of the amount of eligible investment costs for prevention operations carried out collectively by more than one beneficiary 100% Of the amount of eligible investment costs for operations to restore agricultural land and production potential damaged by natural disasters and catastrophic events.	Aims of the measure is to support agricultural holdings' resilience to climate change. This measure supports preventive actions, e.g. investments in drainage systems in northern regions where more rain is expected in the coming years, or in irrigation efficiency in southern regions where more drought and less rain is expected in the coming years.
28	M10) Agri-environment-climate (AEC ă	M 10.1) - Payment for agri-environment-climate commitments (compensation for costs incurred and income foregone) M10.2) - Support for sustainable conservation, use and development of genetic resources in agriculture	Farmers or groups of farmers	600 /ha per year for annual crops 900 /ha per year for specialised perennial crops 450 /ha for other land uses 200 /ha Per livestock unit (LU) per year for local breeds in danger of being lost to farmers	Aim of the measure is to encourage farmers and other land managers to introduce methods of agricultural production compatible with the protection and improvement the environment, the landscape and its characteristics, natural resources, soil, water and biodiversity.
29	M11) Organic farming	M 11.1) - Conversion of conventional farming to organic farming M 11.2) - Maintenance of certified organic farming	Farmers or groups of farmers	600 /ha per year for annual crops 900 /ha per year for specialised perennial crops 450 /ha for other land uses	Organic farming is expected to establish and maintain a sustainable management system for agriculture. The farming practices it promotes contribute to improving soil and water quality, to mitigation and adaptation to climate change and to improved biodiversity (e.g. by avoiding use of synthetic plant protection products and synthetic fertilisers and encouraging crop rotation, use of organic fertilisers and improvement to soil organic matter).

Table 3.4 – *Continued from previous page*

Art.	**Measure**	**Sub measure**	**Beneficiaries**	**Maximum amount (EUR) or rate**	**Potential impacts on agricultural practices and/or climate change adaption**
30	M12) Natura 2000 & Water Framework Directive payments	M12.1) - compensation payment for Natura 2000 agricultural areas M 12.3) - Compensation payment for agricultural areas included in river basin management plans	Farmers	500 /ha per year maximum in the initial period not exceeding five years. 50 /ha per year minimum for Water Framework Directive payments.	The sub-measure provides compensation payments to farmers for the additional costs and income foregone when implementing the Birds, Habitats & Water Framework Directive. The measure is designed to compensate farmers and foresters for the disadvantages they face as a result of mandatory activities they carry out as a result of the legal requirements set out under this directive, compared to the situation of farmers in other areas not affected by these requirements.
35	M16) Cooperation	M 16.1) - Support for the establishment and operation of Operational Groups (OGs) of the EIP for agricultural productivity and sustainability	Operational Groups are expected to consist of partnerships involving a wide variety of stakeholders but most importantly, “*interested actors such as farmers, researchers, advisors and businesses involved in the agriculture and food sector*.” OGs are meant to be bottom-up instruments providing the space for testing innovative ideas and finding solutions for specific issues	The EU Rural Development Regulation does not set specific limits to funding allocations under M16.	Provides support for: ů planning and realising projects implemented by the OGs, ů disseminating the experience and the knowledge gathered as well as the results achieved by the projects supported.
		M 16.2) - Support for pilot projects and for the development of new products, practices, processes and technologies	OGs established under M16.1		Provides support for pilot projects and the development of new products, practices, processes and technologies in the agriculture, food and forestry sectors
39	M17) Risk management tools	M 17.1)	Tool	Risk Coverage	Threshold to trigger compensation Public contribution

Table 3.4 – *Continued from previous page*

Art.	**Measure**	**Sub measure**	**Beneficiaries**	**Maximum amount (EUR) or rate**	**Potential impacts on agricultural practices and/or climate change adaption**	
		M 17.2)	Insurance	Adverse climatic events, animal and plant disease, pest infestation, environmental incident	>20% losses in production	Up to 70% of the insurance premium
		M 17.3) income stabilisation tool	Mutual fund Mutual fund sectorial Mutual fund non-sectorial	Severe drop in farmer's income	>30% losses in production >20% drop in income >30% drop in income	Up to 70% of: Administrative costs of setting up mutual funding Compensation payed by the mutual funds Initial capital stock of the fund

Cross-cutting (covering both CAP pillars)

Cross-compliance (see Annex I, Supplementary materials Chapter 2 for details) is a mechanism that links elements of both pillars of the CAP to farmers' compliance with various basic standards, and good practice. Its mission is essentially to help agriculture to develop sustainably and link the CAP better to other EU policies, including in the area of the environment and climate. The system includes two types of requirements:

- **Statutory Management Requirements** (SMRs): These requirements refer to 13 legislative standards in the field of the environment, food safety, animal and plant health and animal welfare.
- **Good Agricultural and Environmental Condition** (GAEC): The obligation of keeping land in good agricultural and environmental condition refers to a range of standards related to soil protection, maintenance of soil organic matter and structure, avoiding the deterioration of habitats, and water management.

Through the provisions of cross-compliance, when farmers who receive Pillar I direct payments or Pillar II area-based payments do not respect the standards concerned, their payments can be reduced. Cross-compliance thus helps to provide a foundational level of action with regard to the environment and climate (as well as other concerns of EU citizens).

Table 3.5: Cross-compliance rule most direct link to soil and climate

SMR: Statutory management requirement
GAEC: Standards for good agricultural and environmental condition of land

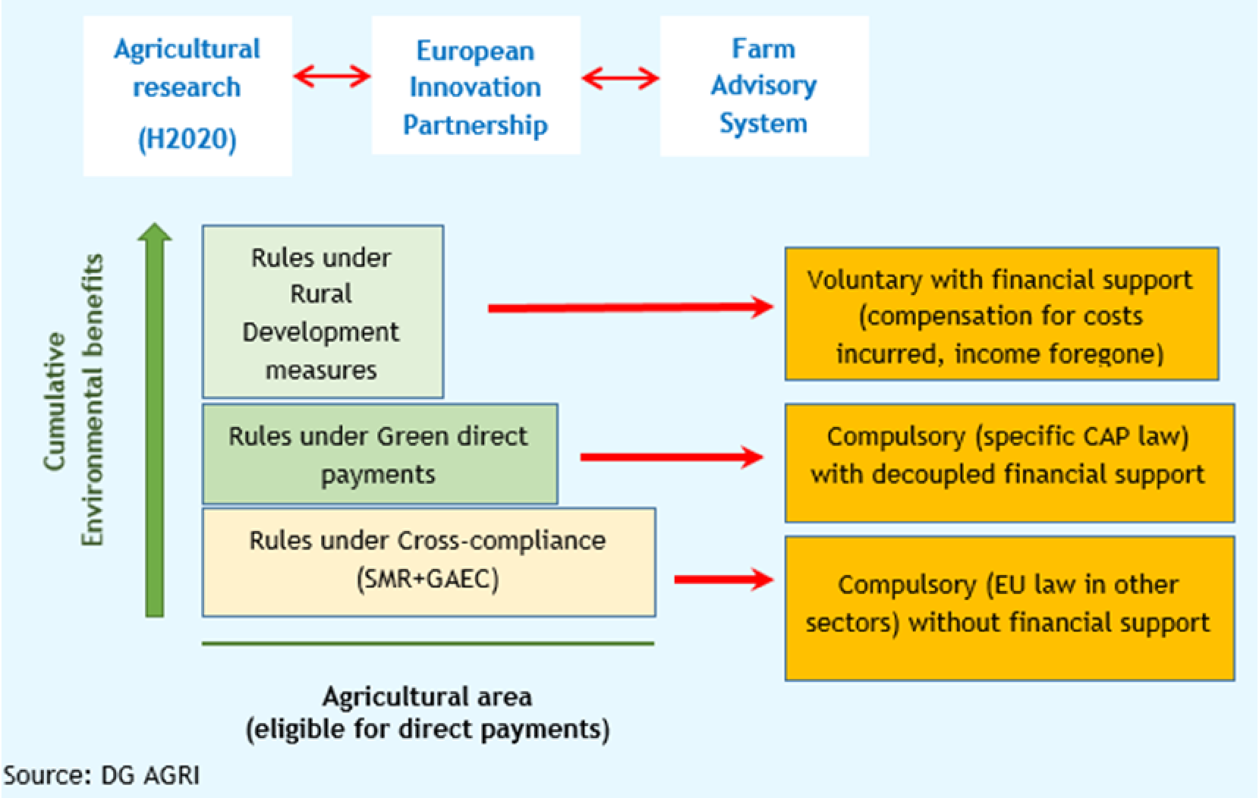
Main Issue	**Requirements and Standards**
Water	SMR 1: Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources
	GAEC 1: Establishment of buffer strips along water courses
	GAEC 2: Where use of water for irrigation is subject to authorisation, compliance with authorisation procedures
	GAEC 3: Protection of ground water against pollution
Soil and carbon stock	GAEC 4: Minimum soil cover
	GAEC 5: Minimum land management reflecting site specific conditions to limit erosion
	GAEC 6: Maintenance of soil organic matter level through appropriate practices including ban on burning arable stubble, except for plant health reasons
Biodiversity	SMR 2: Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds
	SMR 3: Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild flora and fauna.
Landscape, minimum level of maintenance	GAEC 7: Retention of landscape features, including, hedges, ponds, ditches, trees in line, in group or isolated, field margins and terraces, and including a ban on cutting hedges and trees during the bird breeding and rearing season and, as an option, measures for avoiding invasive plant species

Another set of cross-cutting provisions concerns the farm advisory system. All member states are required to set up/designate a farm advisory system (this can be done with the support of a rural development measure – see Section 3.5). In general terms, the farm advisory system should help

CAP beneficiaries become more aware of the relationship between farm practice and management, and various standards. Among the topics on which the farm advisory system must offer advice to farmers[2], the following are directly linked to the environment and climate:

- the rules of cross-compliance;
- the requirements of green direct payments;
- the basic requirements of maintaining agricultural area with regard to eligibility for direct payments
- the Water Framework Directive and
- the Sustainable Use of Pesticides Directive

The combined and complementary effects of various instruments of the I and II pillar define the green architecture of the current CAP. This whole set of complementary policy instruments is accompanied by related training measures and other support from the farm advisory system, insights gained from the European Innovation Partnership and H2020 research, which should help farmers to implement appropriate solutions for their specific situations (Figure 3.4).



Source: DG AGRI

Figure 3.4: The green architecture of the current CAP

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[2] For example, in Italy the Emilia-Romagna Region include in the advisory activities *“Adaptation to climate change due to changes in water regimes”.*

3.5 CAP reform - 2023-2027

On 1 June 2018, the European Commission presented the legislative proposals on the CAP beyond 2020. Following a series of trilogues (“*informal tripartite meetings on legislative proposals between representatives of the Parliament, the Council and the Commission*”) on December 2021, the agreement on reform of the common agricultural policy was formally adopted. The reform covers three regulations, which will generally apply from 1 January 2023 (For the years 2021 and 2022, a transitional regulation is in place, bridging the gap between current and new legislation):

Regulation (EU) 2021/2115 (European Commission, 2021a) of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. The regulation aims to reduce the administrative burdens by the two regulations 1305 and 1307 of the current CAP of Pillar I and II. In particular for Pillar II, EU-level rules for some individual types of support will become less detailed and prescriptive. Overall, more than 20 "measures" and 64 "sub-measures" (i.e. types of support) in the current rules will be slimmed down and combined into eight broad types of intervention to be adapted to territorial and sectorial specificities of EU Member States:

1. environmental, climate and other management commitments;
2. natural or other area-specific constraints;
3. area-specific disadvantages resulting from certain mandatory requirements;
4. investments;
5. installation of young farmers and rural business start-up;
6. risk management tools;
7. cooperation;
8. knowledge exchange and information.

- Regulation (EU) 2021/2116 (European Commission, 2021a) of the European Parliament and of the Council of 2 December 2021 on the financing, management and monitoring of the common agricultural policy and repealing Regulation (EU) No 1306/2013
- Regulation (EU) 2021/2117 (European Commission, 2021a) of the European Parliament and of the Council of 2 December 2021 amending Regulations (EU) No 1308/2013 establishing a common organisation of the markets in agricultural products, (EU) No 1151/2012 on quality schemes for agricultural products and foodstuffs, (EU) No 251/2014 on the definition, description, presentation, labeling and the protection of geographical indications of aromatised wine products and (EU) No 228/2013 laying down specific measures for agriculture in the outermost regions of the Union

The general objectives of the new CAP will be complemented by the cross-cutting objective of modernising the sector by fostering and sharing of knowledge, innovation and digitalisation in agriculture and rural areas, and encouraging their uptake.

The achievement of the general objectives will be pursued through the following specific objectives:

Table 3.6: The 9 specific objectives of the new CAP

Dimension	**Objectives**
Economic	1. support viable farm income and resilience across the Union to enhance food security; 2. enhance market orientation and increase competitiveness, including greater focus on research, technology and digitalisation; 3. improve the farmers' position in the value chain;
Environmental	4. contribute to climate change mitigation and adaptation, as well as sustainable energy; 5. foster sustainable development and efficient management of natural resources such as water, soil and air; 6. contribute to the protection of biodiversity, enhance ecosystem services and preserve habitats and landscapes;
Social	7. attract young farmers and facilitate business development in rural areas; 8. promote employment, growth, social inclusion and local development in rural areas, including bio-economy and sustainable forestry; 9. improve the response of EU agriculture to societal demands on food and health, including safe, nutritious and sustainable food, food waste, as well as animal welfare.
Horizontal	Modernise the sector by fostering and sharing of knowledge, innovation and digitalisation in agriculture and rural areas, and encouraging their uptake

3.5.1 The New Delivery Model

In the implementation the new delivery model (European Commission, 2021c), policy objectives are defined at EU level and Member States are asked to draw up its strategic plan to outline how it intends to reach the EU-wide objective, based on results, rather than on compliance, reflecting the territorial and sectorial specificities of EU Member States. The national strategic plan must be approved by the commission and a performance framework consisting of a set of common context, output, result and impact indicators will be used as the basis for monitoring, evaluation and annual performance reporting Figure 3.5.

Following the principle introduced in the 2013 reform that environmental and climate support should be available under both Pillars I and II of the CAP, the new legislative proposals also set out environmental interventions in both pillars (mandatory for Member States and voluntary for farmers).

3.5.2 Enhanced conditionality

The nature of the enhanced conditionality proposed by the Commission for the CAP post 2022 relevant for soil is shown in the Table 3.4. There are three sets of changes.

- (re-)incorporate the three greening practices into the conditionality, as GAEC 1 permanent pasture, GAEC 8 crop rotation (to replace crop diversification) and GAEC 9 non-productive areas (to replace Ecological Focus Areas).
- the addition of new GAEC 2 to protect carbon-rich soils, and GAEC 10 the ban on converting grassland in Natura 2000 sites.

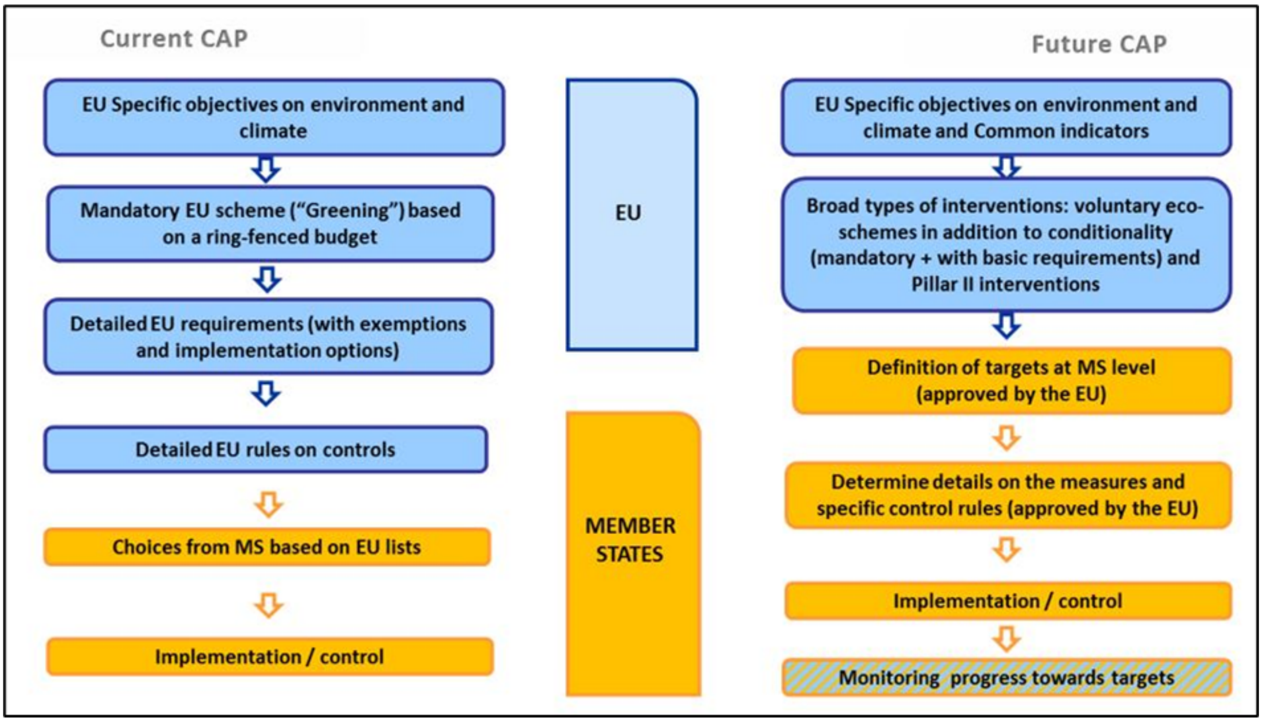


Figure 3.5: Comparison of current and future CAP governance model. *Source: European Commission SWD (2018) 301 final*

- the addition of SMR 1 (water) and 13 (pesticide)

Table 3.7: New Requirements and standards in the enhanced conditionality

Areas	**Main Issue**	**Requirements and standards**	
Climate and environment			
Climate change (mitigation of and adaptation to)	GAEC 1	Maintenance of permanent grassland based on a ratio of permanent grassland in relation to agricultural area	***New (ex greening)***
	GAEC 2	Appropriate protection of wetland and peatland	***new***
	GAEC 3	Ban on burning arable stubble, except for plant health reasons	***Ex GAEC 6***
Water	SMR 1	Directive 2000/60/EC of 23 October 2000 of the European Parliament and of the Council establishing a framework for Community action in the field of water policy:	***new***
	SMR 2	Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (OJ L 375, 31.12.1991, p. 1): Articles 4 and 5	**Ex SMR 1**
	GAEC 4	Establishment of buffer strips along water courses	***Ex GAEC 1***
Soil (protection and quality)	GAEC 6	Tillage management reducing the risk of soil degradation, including slope consideration	***Ex GAEC 5***
	GAEC 7	No bare soil in most sensitive period(s)	***Ex GAEC 4***
	GAEC 8	Crop rotation	***New (repalace crop diversification)***
Biodiversity and landscape (protection and quality)	SMR 3	Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (OJ L 20, 26.1.2010, p. 7):	**Ex SMR 2**
	SMR 4	Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild flora and fauna (OJ L 206, 22.7.1992, p. 7):	**Ex SMR 3**
	GAEC 9	Minimum share of agricultural area devoted to non-productive features or areas	***New (ex EFA greening)***
		• Retention of landscape features • Ban on cutting hedges and trees during the bird breeding and rearing season • As an option, measures for avoiding invasive plant species	***EX GAEC 7***
	GAEC 10	Ban on converting or ploughing permanent grassland in Natura 2000 sites	***new***
Public health, animal health and plant health			
Plant protection products	SMR 12	Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC (OJ L 309, 24.11.2009, p. 1):	***Ex SMR 10***

Table 3.7 – *Continued from previous page*

Areas	Main Issue	Requirements and standards	
	SMR 13	Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides (OJ L 309, 24.11.2009, p. 71):	***new***

3.5.3 Eco-scheme

The proposal for the eco-scheme under Pillar 1 constitutes the main new feature of the green architecture, replacing the green direct payments introduced in the 2014-2020 CAP. Under the proposals, Member States are required to put in place the eco-scheme, designed to address their regional or national environmental and climate needs and contribute to the CAP's environmental and climate objectives. This moves away from the approach taken with the green direct payments whereby Member States implemented a common set of practices with detailed rules set at EU level, applicable to all eligible farmers in receipt of direct payments. The proposed eco-scheme measures therefore gives Member States more flexibility to better take into account local conditions. The other key difference is that, unlike the green direct payments' regime, which was mandatory for eligible farmers to participate in if they wished to receive payments, the eco-scheme would be voluntary for farmers to enter into. The new green architecture in shown in Figure 3.6.

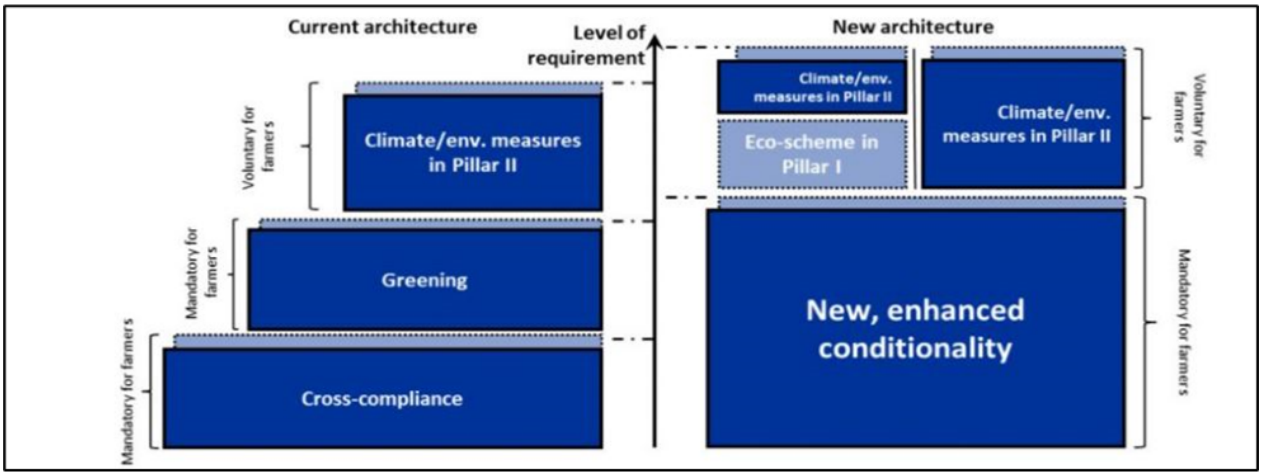


Figure 3.6: Comparison of the CAP's current and proposed new green architecture *Source: European Commission SWD (2018) 301 final*

As part of the preparatory work for the reform, the Commission has published a factsheet (European Comission, 2021) with a proposal list of agricultural practices that eco-schemes could support in the future CAP national strategic plans, to fulfill Green Deal, the Farm to fork strategy and Biodiversity strategies and the climate and environmental specific objectives (SO) of the new CAP (Figure 3.7):

- **SO 4:** Contribute to climate change mitigation and adaptation, as well as sustainable energy
- **SO 5:** Foster sustainable development and efficient management of natural resources such as water, soil and air

- **SO 6:** Contribute to the protection of biodiversity, enhance ecosystem services and preserve habitats and landscapes
- **SO 9**: Improve animal welfare and address antimicrobial resistance

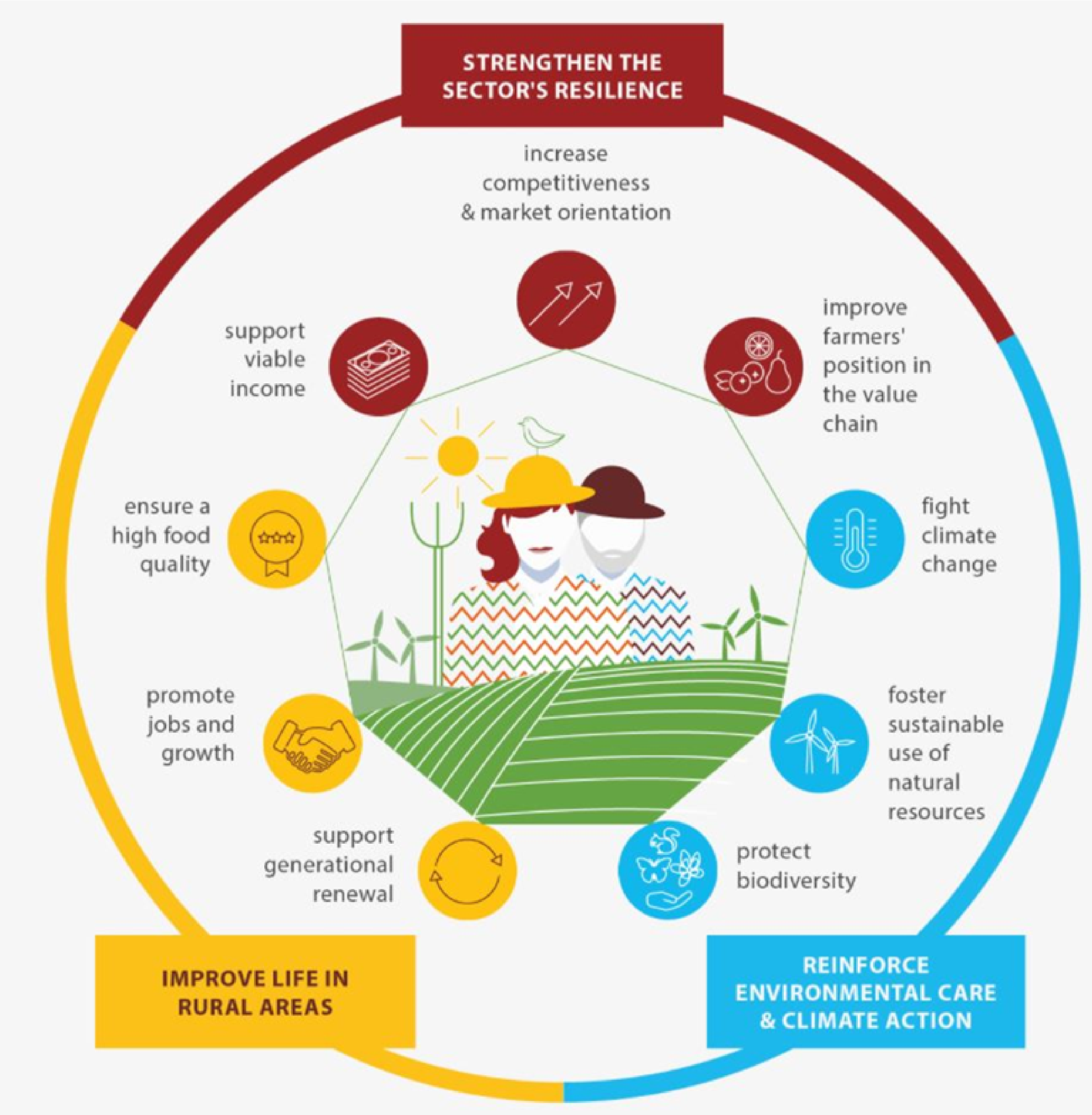


Figure 3.7: The 9 objectives of the new Common Agricultural Policy and its three dimensions
Source: European Council - Infographic - The future of EU agricultural policy

Eleven categories of beneficial practices are listed, substantially divided into two groups: those already codified within EU policy tools (Organic farming, Integrated Pest Management) and "other practices".

The prosed eco-schemes address one or more areas of environment, climate and animal welfare actions under the cap strategic plans:

a) Climate change mitigation: reduction of GHG emissions from agriculture, conservation carbon stocks, carbon sequestration;

b) Adaptation to climate change: increasing the resilience of food systems and diversity animal and plant for greater resistance to disease and climate change

c) Protection or improvement of water quality and reduction of pressure on water resources

d) Prevention of soil degradation, soil restoration, improvement of soil fertility and of nutrient management

e) Protection of biodiversity, conservation or restoration of habitats or species, including maintenance and creation of landscape features or non-productive areas

f) Actions for a sustainable and reduced use of pesticides, particularly pesticides that present a risk for human health or environment

g) Actions to enhance animal welfare or address antimicrobial resistance

Among the eleven categories of practices, several may have a positive direct/indirect impact on sustainable soil management practices and climate adaptation in general (areas from b to f):

- *Agro-ecology including:*
    - Crop rotation with leguminous crops (a, b, d, f)
    - Mixed cropping - multi cropping (b, d, e, f)
    - Cover crop between tree rows on permanent crops - orchards, vineyards, olive trees - above conditionality (a, c, d, e, f)
    - Winter soil cover and catch crops above conditionality (a, b, c, d)
    - Low intensity grass-based livestock system (a, c, d, g)
    - Use of crops/plant varieties more resilient to climate change (b, c, e, f)
    - Mixed species/diverse sward of permanent grassland for biodiversity purpose (pollination, birds, game feedstocks) (c, d, e, f)
- *High nature value (HNV) farming including*
    - Land lying fallow with species composition for biodiversity purpose (pollination, birds, game feedstocks, etc.) (c, e, f)
    - Reduction of fertilizer use, low intensity management in arable crops (a, b, c, d, e, f, g)
- *Carbon farming including*
    - Conservation agriculture (a, d)
    - Rewetting wetlands/peatlands, paludiculture (a, c, d, e)
    - Appropriate management of residues, i.e. burying of agricultural residues, seeding on residues (a, c, d)
    - Establishment and maintenance of permanent grassland (a, c, d, e, f)
    - Extensive use of permanent grassland (a, c, d)

- *Precision farming including*
  - Nutrients management plan, use of innovative approaches to minimise nutrient release, optimal pH for nutrient uptake, circular agriculture (a, c, d, f)
  - Precision crop farming to reduce inputs (fertilisers, water, plant protection products) (e, f)
  - Improving irrigation efficiency (b)
- *Improve nutrient management, including*
  - implementation of nitrates-related measures that go beyond the conditionality obligations (c, d, e,)
  - measures to reduce and prevent water, air and soil pollution from excess nutrients such as soil sampling if not already obligatory, creation of nutrient traps (c, d, e,)
- *Protecting water resources, including*
  - Managing crop water demand (switching to less water intensive crops, changing planting dates, optimised irrigation schedules) (b)
- *Other practices beneficial for soil, including*
  - Erosion prevention strips and wind breaks (b, d, e,)
  - Establishment or maintenance of terraces and strip cropping (b, d, e,)

3.6 The European Green Deal

The European Green Deal (European Commssion, 2019) proposal is comprehensive and ambitious. It defines a roadmap in the form of several key actions outlined in various strategies (Figure 3.8). Some of them, notably the EU Biodiversity Strategy for 2030 and related EU Soil Strategy for 2030 (European Commssion, 2021), the Farm to fork strategy (European Commssion, 2020) and the various climate texts, could affect European agriculture (and soil management practices) and food in a significant way (GUYOMARD and BUREAU, 2020).

Soils will play an important role in the future agricultural policy (Farm to Fork strategy), environmental protection (Biodiversity strategy) and climate change (Climate Law). Key actions in the Green Deal roadmap with significant potential impacts for soil management and climate adaption are summarized in the following table.

3.7 Nitrate Directive

3.7.1 Rationale and objectives

The Nitrates Directive (European Commission, 1991) aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting

Table 3.8: Green Deal Key actions with potential importance for soil management climate adaption

Key action roadmap	Potential importance for soil management	Potential importance for climate adaption
Climate ambition		
European Climate Law - New EU Strategy on Adaptation to Climate Change		Could potentially affect CAP measures aimed at favouring farmers' adaptation to climate change
Greening the CAP / "Farm to Fork Strategy"		
• Reduce by 50% the overall use and risk of chemical pesticides and reduce use by 50% of more hazardous pesticides by 2030 • Reduce nutrient losses by at least 50%; reduce use of fertilisers by at least 20 % by 2030	Protect soil against pollution, enhance soil nutrient use efficiency	Promote actions to develop innovative ways, to adapt to climate change and improve sustainability of food systems.
• Achieve at least 25% of the EU's agricultural land under organic farming by 2030	Promote SSP	
Preserving and protecting biodiversity		
EU Biodiversity Strategy for 2030 • set a minimum of 30 % of the EU's land area as protected areas • back at least 10 % of agricultural area under high-diversity landscape features	Healthy soils – new EU soil strategy The goals are to: • protect soil fertility • reduce erosion and sealing • increase organic matter • identify contaminated sites • restore degraded soils • define what constitutes 'good ecological status' for soils	

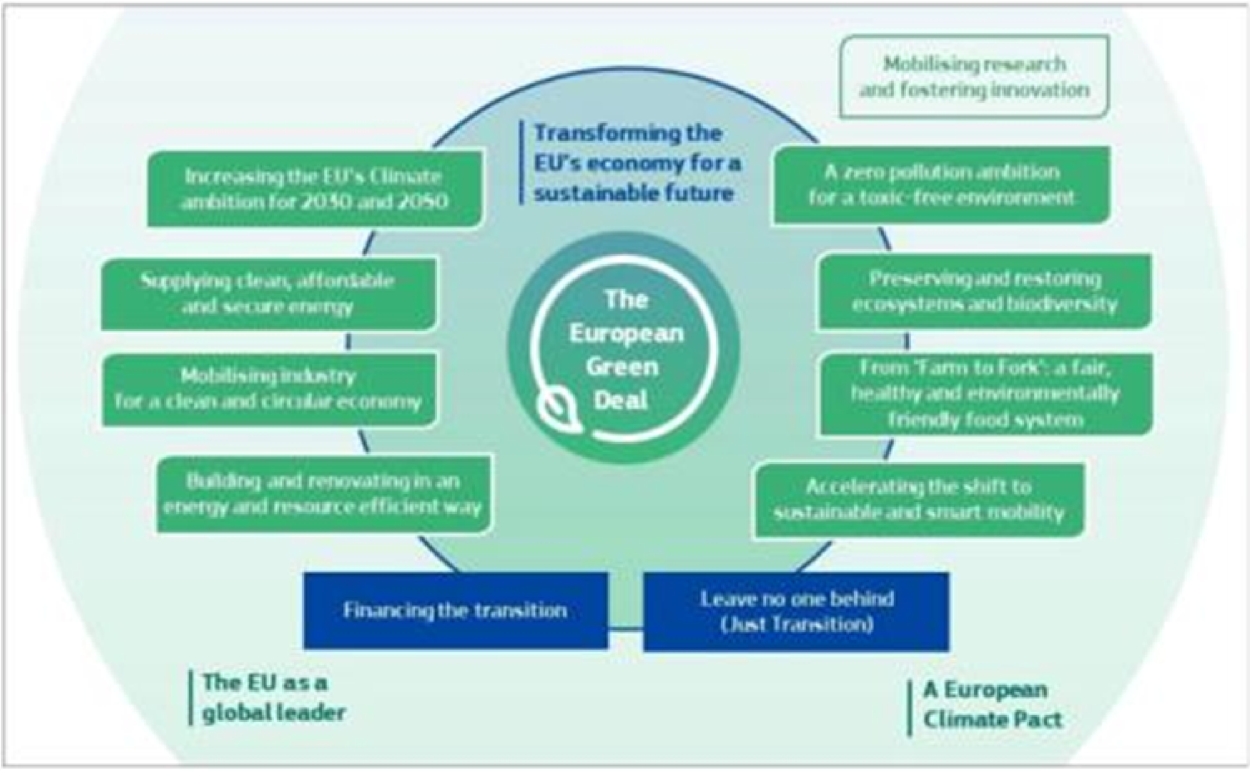


Figure 3.8: The various elements of the European Green Deal. *Source: COM(2019) 640 final*

the use of good farming practices. While nitrogen is a vital nutrient that helps plants and crops to grow, high concentrations are harmful to people and nature. The agricultural use of nitrates in organic and chemical fertilisers has been a major source of water pollution in Europe. As water sources are not restricted within national boundaries, an EU wide approach was crucial to tackling the problem of pollution.

The Nitrate Directive obliges Member States to designate Nitrate Vulnerable Zones (NVZ) of all known areas in Member States whose waters – including groundwater – are or are likely to be affected by nitrate pollution. Vulnerable zones are defined as those waters which contain a nitrates concentration of more than 50 mg/l or are susceptible to contain such nitrates concentration if measures are not taken. Under the Nitrates Directive, all Member States have to:

- Designate as NVZs areas of land which drain into polluted waters or waters at risk of pollution and which contribute to nitrate pollution. Member States can also choose to apply measures to the whole territory (instead of designating NVZs), based on art. 3.5 of the directive (Austria, Denmark, Finland, Germany, Ireland, Lithuania, Luxembourg, Malta, the Netherlands, Romania, Slovenia, the Region of Flanders and Northern Ireland have followed this approach).
- Establish of Codes of Good Agricultural Practice to be implemented by farmers on a voluntary basis: It sets out various good practices, such as measures limiting the periods when nitrogen fertilizers can be applied on land; measures limiting the conditions for fertilizer application to prevent nitrate losses from leaching and run-off; requirement for a minimum storage capacity for livestock manure; and crop rotations, soil winter cover, and catch crops to prevent nitrate leaching and run-off during wet seasons.
- Establish of action programmes to be implemented by farmers within NVZs on a compulsory basis, considering available scientific and technical data and overall environmental conditions.

Action programmes must include measures already included in Codes of Good Agricultural Practice, which become mandatory in NVZs; and other measures, such as limitation of fertilizer application (mineral and organic), considering crop needs, all nitrogen inputs and soil nitrogen supply, maximum amount of livestock manure to be applied (corresponding to 170 kg nitrogen/hectare/year).

- Carry out a comprehensive monitoring programme and submit every 4 years, a report on the implementation of the Directive. The report includes information on nitrate-vulnerable zones, results of water monitoring, and a summary of the relevant aspects of codes of good agricultural practices and action programmes; The Nitrate Directive has been in place since 19 December 1991. The successive amendments and corrigenda to the Directive have been incorporated into the original text (Regulation (EC) No 1882/2003 and Regulation (EC) No 1137/2008). It is applied at European level and has been transposed to national law by member states. Member states must establish and present to the European Commission reports every 4 years on the implementation of this Directive and the commission should report regularly on the implementation of this Directive by the member states.

Geographical coverage: The Nitrate Directive has been designed at EU level and implemented at national or local scale depending on the choice made by the Member States, as shown in figure 6.

Targeted actors: The Nitrate Directive involves both public and private sectors: it is targeted to national/regional authorities, in charge of promoting local activities and strategies (planning, monitoring, etc.) as well as to farmers, asked to adopt new farming strategies (best practices) in order to reduce the pollution of nitrate.

Financial issues: No specific funds have been invested, even if specific rural development measures of agri-environment-climate payments were dedicated to nitrate rate reduction.

3.8 Water Framework Directive (WFD)

3.8.1 Rationale and objectives

The Water Framework Directive (European Commission, 2000) represents the cornerstone of EU water protection policy, which requires that all EU waters should achieve good status by 2015. It seeks to provide a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. In doing so the WFD aims to help improve freshwater quality and quantity, protect the environment and ecosystems and reduce water pollution. One of the major challenges to achieve these objectives is represented by the pollutants released into the aquatic environment from a variety of sources including agriculture, industry and incineration. The WFD aims to protect and improve the quality of water in Europe.

The WFD relates to the quality of fresh and coastal waters in EU, aiming to attain good ecological and chemical status of Europe’s fresh and coastal waters. Specifically, this includes; protecting all forms of water (inland, surface, transitional, coastal and ground); restoring the ecosystems in and around these water bodies; reducing pollution in water bodies, and; guaranteeing sustainable water use by individuals and businesses.

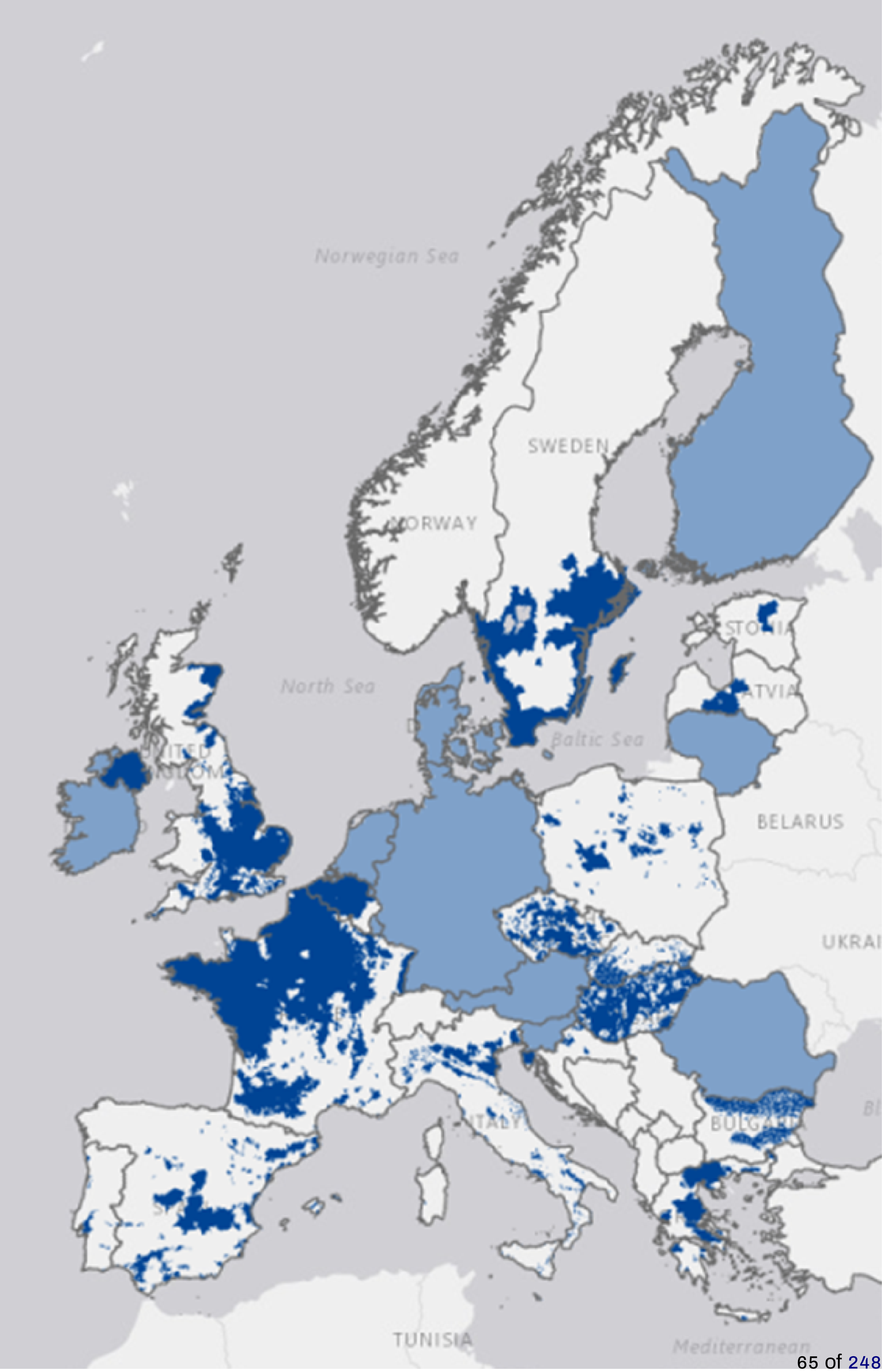


Figure 3.9: Nitrate vulnerable zones. Source: JRC

The WFD requires all Member States to protect and improve water quality in all waters in order to achieve good ecological status. The legislation places clear responsibilities on national authorities. They are asked for:

- identify the individual river basins on their territory - that is, the surrounding land areas that drain into river systems;
- designate authorities to manage these basins in line with the EU rules;
- analyse the features of each river basin, including the impact of human activity and an economic assessment of water use;
- monitor the status of the water in each basin;
- register protected areas, such as those used for drinking water, which require special attention;
- develop and implement “river-basin management plans” to prevent deterioration of surface water, protect and enhance groundwater and preserve protected areas. River-basin management plans include a programme of measures to be implemented in the plan horizon, that shall correspond to a cost-effective approach to achieve established objectives;
- ensure the cost of water services is recovered so that the resources are used efficiently, and polluters pay;
- provide public information and consultation on their river-basin management plans.

Geographical coverage: The WFD must be adopted at the level of the member states. The territorial entity, in which it is implemented was the river basin, now evolved in the concept of ‘river basin district’. For each river basin district - some of which will traverse national frontiers - a "river basin management plan" needs to be established and updated every six years.

Targeted actors: The WFD regards member state strategies. Even though actions and measures in river basin management plans aimed at increased water quality status are targeted on national or local policies, they also affect farmer activity directly and indirectly. Irrigation consortia for instance, are asked to provide more efficient water pricing policies able to reflect the whole (economic, social and environmental) value of water and also to plan actions for a better control of irrigation volumes.

Financial issues: One of the most innovative elements of the Water-Framework Directive is the important role that economic analysis is assigned in achieving its environmental objectives. Full recovery and polluter’s pay principle, environmental and resource costs, are some of the main economic issues that WFD promote to gain a fair allocation of scarce water resources, also under economic perspective. No specific founds have been invested to perform such economic analysis, even if specific rural development measures were dedicated to the requirements of WFD. Subsidies for the farmers action or constraints due to WFD were established, for example, in Measure 12.

Although climate change is not explicitly included in the text of the WFD, the cyclical approach of the river basin management planning process makes it well suited to adaptively manage climate change impacts. Steps in the river basin management planning process provide a structure for incorporating adaptation to climate change through: risk appraisal, monitoring and assessment, objective setting, economic analysis and Programmes of Measures to achieve environmental objectives (European Comission, 2000).

3.9 Sustainable use of Pesticide Directive (PD)

3.9.1 Rationale and objectives

The Sustainable use of pesticide Directive (European Commssion, 2009) requires Member States to implement policies and actions to reduce the risks and impacts of pesticide use on human health, the environment and biodiversity. These policies must ensure the development and introduction of agricultural techniques that reduce reliance on pesticides, thereby lessening their risks and impacts on human health and the environment, encouraging the uptake of integrated pest management and alternative approaches or techniques, such as organic farming and the use of non-chemical alternatives to pesticides.

EU countries have drawn up National Action Plans, to implement the range of actions set out in the Directive, the main actions relate to:

- training of users, advisors and distributors
- inspection of pesticide application equipment
- the prohibition of aerial spraying
- the protection of the aquatic environment and drinking water
- limitation of pesticide use in sensitive areas
- information and awareness raising about pesticide risks
- systems for gathering information on pesticide acute poisoning incidents, as well as chronic poisoning developments, where available

Geographical coverage: The pesticide directive has been designed at EU level and implemented at national and local scale.

Targeted actors: The main entities involved in the implementation of the National Action Plans are Ministry (Agricultural, Food and Forestry Policies, Environment, Health, Education, University and Research), and local (Regions, Provinces, Municipalities, entities managing Natura 2000 sites and protected areas) administration. Farmers and any other pesticide users, producers and distributors are the recipients of the rules established in the National Plan.

Financial issues: specific economic instruments set out in the National Action Plans.

3.10 Relevance of policy measures and instruments addressing soil related issues

3.10.1 Common Agricultural Policy

The CAP provides various instruments and measures that may impact sustainable soil management and soil quality. The link to agricultural practices that improve soil quality is potentially substantial because two focus areas specifically target soil:

- Focus area 4C preventing soil erosion and improving soil management
- Focus area 5E fostering carbon conservation and sequestration in agriculture

The Rural Development Regulation sets a total of 20 support measures, a number of which may contribute to sustainable soil management (not considering those related to forest management).

- commitments into agri-environment and climate measures (AECMs: M10),
- support for organic farming (M11)

Other rural development measures may indirectly contribute to fostering sustainable soil management, in particular investments in physical assets (M4), knowledge transfer and information actions (M1); advisory services, farm management (M2); Natura 2000 and Water Framework Directive (M12); payments to areas facing natural or other specific constraints (M13); and Cooperation (M16).

The above-described instruments and measures and its link with the CAP soil-related objectives, and the expected impact area summarized in Figure 3.10.

3.10.2 Impact of CAP on climate change and greenhouse gas emission

Agriculture is highly vulnerable to the impacts of climate change (e.g. crop failures and tree dieback from droughts, storms, floods, or pest and disease outbreaks) and is facing increasing climate-related risks. The farming sector needs to adapt to climate change (by, for example, improving soil quality and water management, establishing hedge rows, planting more resilient crop varieties, and adopting more diverse crop rotation practices) to secure future yields (European Commission, 2021b).

EU climate policy in the 2014-2020 period was also shaped by the EU strategy on adaptation to climate change. It encouraged Member States to adopt comprehensive adaptation strategies, to build up their adaptation capacities and to take adaptation action in key vulnerable sectors, including agriculture (through insurance against natural and man-made disasters, for instance). Furthermore,

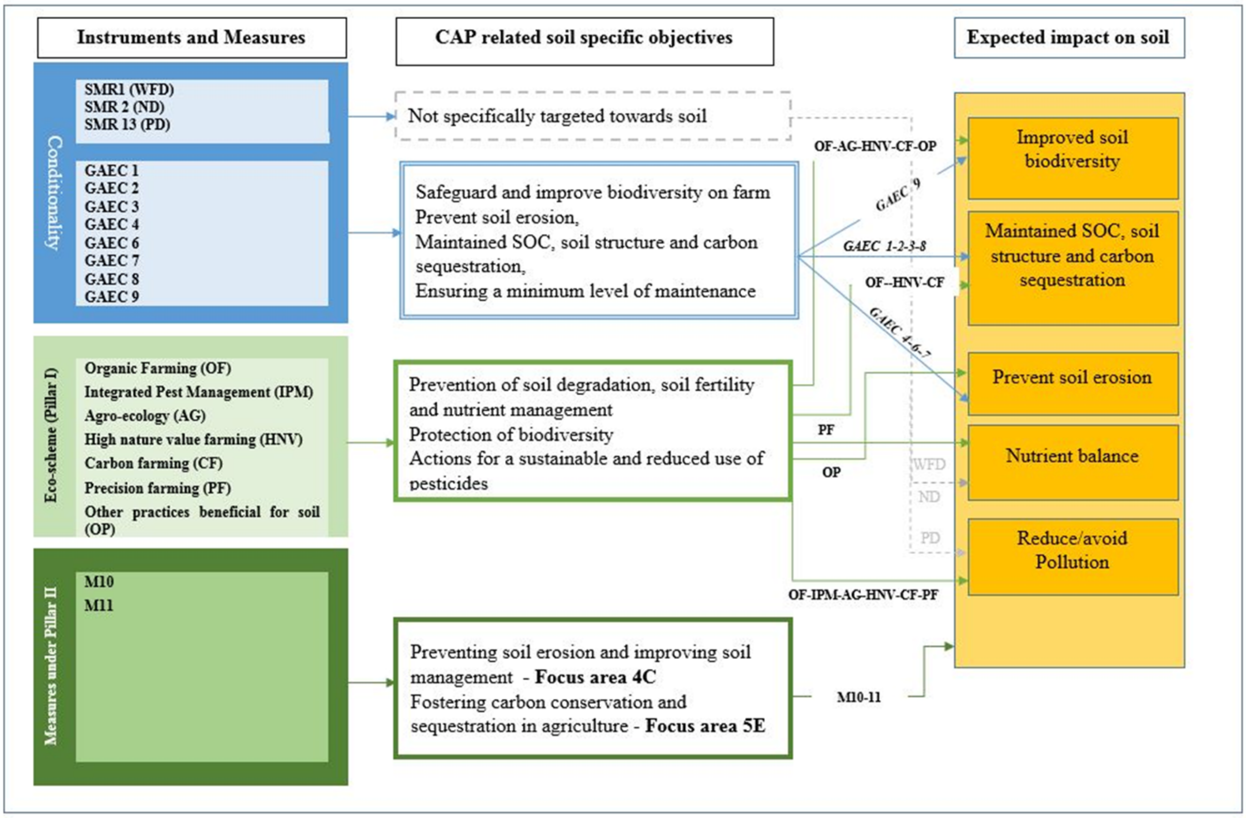


Figure 3.10: Relevance of policy measures and instruments addressing soil related issues

it helped address the existing knowledge gaps on adaptation in the agricultural sector. On 24 February 2021 the Commission announced a new, even more ambitious EU Strategy on Adaptation to Climate Change, which commits the EU and Member States to make continuous progress to boost adaptive capacity, strengthen resilience and reduce vulnerability to climate change.

According to the main considerations highlighted in a Commission Working document (Commission, 2021), which closes an assessment process on the impact of the CAP on climate change and greenhouse gas emissions conducted between 2017 and 2020, the greatest adaptation effects, are guaranteed by the measures that support the diversification of agricultural systems, the implementation of dedicated investments and the adoption of cultivation practices aimed at limiting soil erosion, as well as those related to the risk management.

The following section summarizes the main findings of the aforementioned document on the impact of CAP on climate adaptation.

3.10.3 Effects of the Horizontal Regulations on adaptation

SMR1 (WFD): is intended to promote the efficient use of irrigation to protect water (in quality and quantity) that could have a great impact to climate change adaptation.

GAEC1 The permanent grassland ratio (PG) can improve adaptation, since permanent grass cover limits soil erosion and improves resilience to floods. It helps to maintain a level of diversity in farming systems, which has been identified as crucial for adaptation.

GAEC6 (maintenance of soil organic matter) is the most likely to benefit adaptation

GAEC8 (Crop rotation) is likely to have positive effects on adaptation by agricultural holdings and on territorial adaptation. Increased crop diversity and crop rotation promoted by the measure improve farms' resilience to climatic events such as droughts and to economic shocks from price volatility. Crop rotation also helps to improve soil quality and resilience to pests, while diversifying into less water-demanding crops may lower dependence on water resources in traditionally irrigated areas.

GAEC9 (EFA), planting of catch/cover crops, adopted by many farmers to comply with the obligation, favours adaptation by improving soil organic carbon content and maintaining soil moisture, which is good for resilience to droughts, while also limiting the risk of soil erosion. The maintenance of (non-bare) fallow land and landscape elements is also beneficial for resilience to floods and protection from soil erosion.

Farm Advisory System (FAS), climate change has been included in the scope of the FAS from 2014, it is difficult to assess accurately to what extent climate change has been included in advice to farmers due to high complexity in advising on adaptation given: 1) the uncertainty of climate change impacts; 2) the fact that knowledge of adaptation issues is still developing; and 3) the fact that the vulnerability of a given farming system is very dependent on its context and location.

3.10.4 Effects of the I pillar's measures on adaptation

Eco-Scheme: This new instrument introduced in the CAP reform is intended to promote agricultural practices to climate change mitigation and adaptation.

3.10.5 Effects of the II pillar's measures on adaptation

Soft measures **Training (measure 1) and advisory services (measure 2):** climate change adaptation is often mentioned as an objective of these measures, but most supported actions focused primarily on economic or other environmental subjects. Furthermore, the effects of the measures have been hindered by a low level of programming and delays in implementation, which is problematic given the fact that, in several Member States or regions, there is no funding allocated to training activities beyond rural development support.

Cooperation (measure 16) can promote adaptation to climate change thanks to support for the development and diffusion of innovative practices, better planning of resource management and support for diversification of agricultural holdings' activities.

Measure 19 (LEADER): a review of LEADER projects supported in the previous programming period (2007-2013) across the EU-28 showed that, overall, climate-relevant projects mostly focused on capacity building and energy efficiency, with a limited focus on more explicit adaptation activities (Frelih-Larsen et al., 2014) .

Investment measures **Measure 4 (investments in physical assets)** has strong potential to support climate change adaptation, since investment in equipment and infrastructure can enable vulnerable farms and forest holdings to adapt to climate change through, for instance:

- improved resource efficiency for agricultural holdings (water efficiency, reduced soil tillage);
- storage facilities to increase water resource availability in agricultural holdings (including rain water collection);
- modernisation of livestock production units (recycling water or improving ventilation of buildings).

Non-productive investments linked to the achievement of agri-environment-climate objectives are also very relevant for climate change adaptation. Support is available, for instance, for the planting of hedges and trees against erosion, or the restoration of wetlands or peatland.

Risk management measures *Risk is inherent in agriculture*

Agricultural activities have a strong link with climate. Weather conditions can either boost or hinder production. According to the European Environment Agency, crop losses in the EU as a result of extreme weather conditions are in danger of increasing (European Environment Agency, 2015).

The recent growth in the frequency of extreme natural events and the processes of globalization of international markets increase the risk exposure of farmer. The increased uncertainty can cause the propensity to invest to contract and, in extreme cases, even facilitate the abandonment of the activity.

How risks such as production losses and price volatility are addressed depends on their frequency and impact. In its analysis, the Commission refers to a risk classification developed by the organisation for economic co-operation and development (OECD, 2011), setting out where risks should be faced by farmers alone, by means of for example, insurance mechanisms, and where they should be addressed through public intervention.

The CAP policy instruments most likely addressing risk management in agriculture are :

Measure 5 - disaster risk reduction, which aims to support agricultural holdings' resilience to climate change. This measure supports preventive actions, e.g. investments in drainage systems in northern regions where more rain is expected in the coming years

M17: Risk management, support under this measure shall cover:

1. financial contributions to premiums for crop, animal and plant insurance against economic losses to farmers caused by adverse climatic events, animal or plant diseases, pest infestation, or an environmental incident (Sub-measure17.1);
2. financial contributions to mutual funds to pay financial compensations to farmers, for economic losses caused by adverse climatic events or by the outbreak of an animal or plant disease or pest infestation or an environmental incident (Sub-measure17.2);
3. an Income Stabilization Tool, in the form of financial contributions to mutual funds, providing compensation to farmers for a severe drop in their income (Sub-measure17.3).

Table 3.9: Different categories of risks faced by farms and related instruments. *Source*: (European Court of Auditors, 2019)

Risk categories	Instruments
Normal risks: events that occur frequently, locally and generally with low damage	**Managed at farm level:** crop rotation, more resistant/adapted species/varieties, savings, sanitary and phytosanitary measures, production diversification (including off-farm work), prevention investments (e.g. sustainable irrigation systems, hail protection) **Ex-ante public support (EU/MS):** subsidised prevention investment, preventing measures and monitoring of diseases, advisory, training and awareness services, EU direct payments
Marketable risks: less frequent events, but more difficult for farmers to manage on their ow	**Managed through market tools**: private market instruments (insurance, forward and future contracts) or shared with other farmers (mutual funds) or cooperatives or producer organisations **Ex-ante public support (EU/MS):** EU/MS subsidised insurance and mutual funds, CAP market measures
Catastrophic risks: Event that occur rarely but are systemic and cause large-scale damage	**Managed through public interventions**: **Ex-post public support (EU/MS):** CAP exceptional measures, other EU funds, ad-hoc aid

For the purpose of points (b) and (c), 'mutual fund' means a scheme accredited by the Member State in accordance with its national law for affiliated farmers to insure themselves, whereby compensation payments are made to affiliated farmers for economic losses caused by the outbreak of adverse climatic events or an animal or plant disease or pest infestation or an environmental incident, or for a severe drop in their income.

Land management measures The **agri-environment-climate measure (AECM – measure 10)** has diverse potential effects on adaptation. A number of interventions under this measure help to improve the resilience of farms and society more generally by establishing areas of semi-natural vegetation and landscape elements, and by promoting practices that improve soil health and water retention in soils, limit soil erosion, improve resilience to floods, etc. For instance, cover crops, crop rotation, improved management of landscape features, zero tillage and increased use of forage crops are some practices that can be promoted by this measure and which can, in certain circumstances, be beneficial for adaptation. Furthermore, the measure may also improve resilience thanks to the conservation, use and development of varieties more resilient to droughts.

Organic farming (measure 11) has the potential to build resilient food systems, mainly through crop rotation/diversification and improved soil quality. 8.0% of EU agricultural area is farmed organically and close to 65% of this area is covered by EU organic support.

Natura 2000 and Water Framework Directive payments (measure 12) can contribute to territorial adaptation through the protection of biodiversity and wetlands,

Areas facing natural or specific constraints (ANC – measure 13) supports the maintenance of farms in remote areas, thus limiting land abandonment and preventing higher fire risk. Importantly, it maintains a diversity of products, farming systems and habitats (including grassland) that is deemed important for adaptation at a higher level (by regions and EU society).

An attempt to make a link of the contribution of sustainable soil management practices to objectives put forward by EU agro-environmental policies, and the relevance of CAP measures climate adaption, is reported in Figure 3.11 and Figure 3.12 respectively.

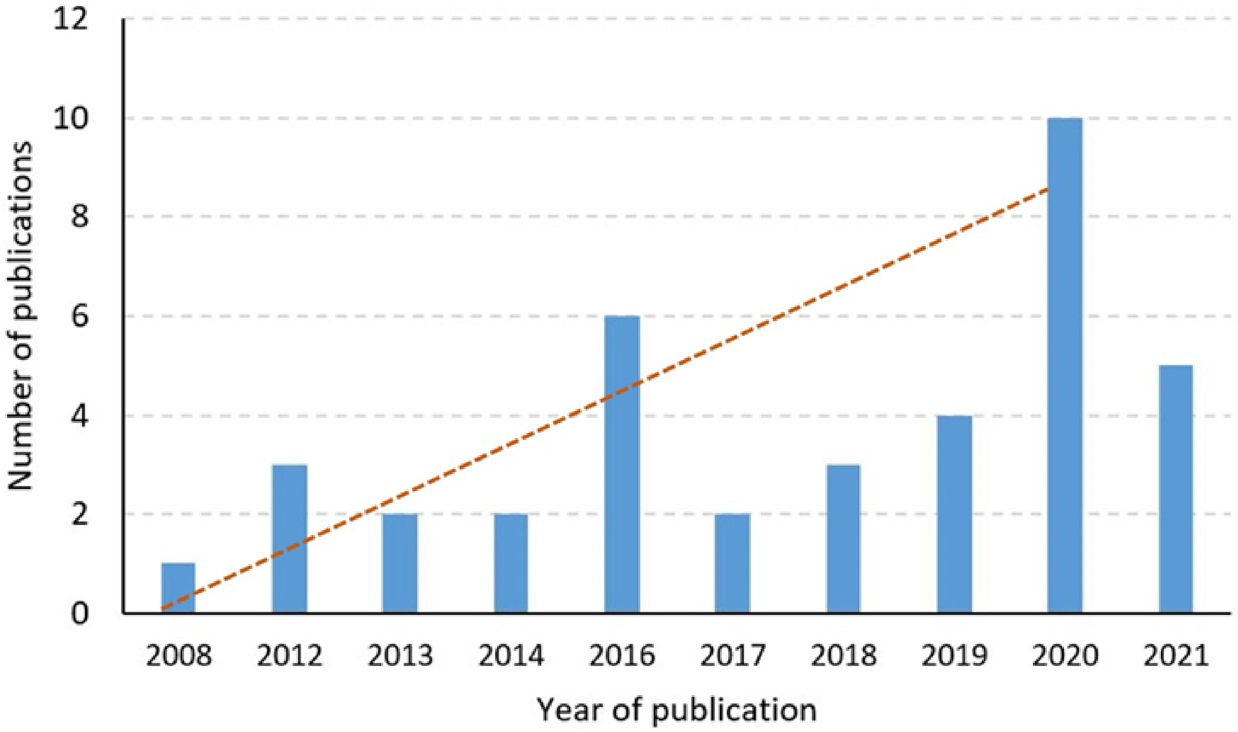
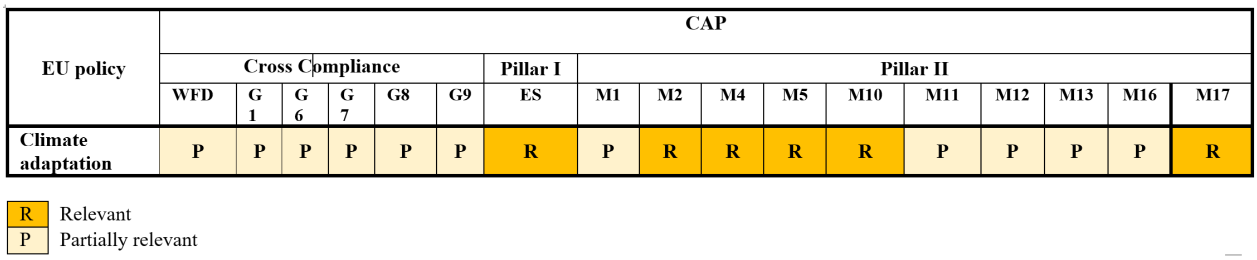


Figure 3.11: Contribution of SSP to objectives put forward by EU agro-environmental policies



EU policy	CAP																
	Cross Compliance						Pillar I	Pillar II									
	WFD	G 1	G 6	G 7	G8	G9	ES	M1	M2	M4	M5	M10	M11	M12	M13	M16	M17
Climate adaptation	P	P	P	P	P	P	R	P	R	R	R	R	P	P	P	P	R

R Relevant
P Partially relevant

Figure 3.12: Relevance of CAP measures to climate adaptation. *Source: Our adaptation from SWD(2021) 115 final*

3.11 Conclusion

Agriculture is highly vulnerable to the impacts of climate change; the farming sector needs to adapt to climate change. Soil management is one tool farmers have to respond (adapt) to climate change. Public policies play an important role in farmers' decisions influencing sustainability of crop production. The potential solutions, that are relevant for the CLIMASOMA project, offered by policies at various governance levels for adapting to climate change, namely through programmes and by introducing adaptation measures at farm level, have been identified in the inventory. Examples of integration of adaptation into the current and proposed CAP framework 2023-2027, are (Jacobs et al., 2019):

CAP 2014-2022 Indirect support for adaptation in cross-compliance regime and greening provision. The cross-compliance standards with the most direct link to soil are GAEC standards 4 (minimum soil cover), 5 (minimum land management to limit erosion) and 6 (maintenance of soil organic matter). SMR 1 (on the Nitrates Directive) and GAEC standard 7 (landscape features) are also relevant.

The link to agricultural practices that improve soil quality is potentially substantial because two focus areas of rural development programme specifically target soil:

- Focus area 4C preventing soil erosion and improving soil management
- Focus area 5E fostering carbon conservation and sequestration in agriculture

The Rural Development Regulation sets a total of 20 support measures, a number of which may contribute to sustainable soil management (not considering those related to forest management), in particular;

The farm advisory system (FAS) is obligatory under the CAP and aims to help farmers better understand and meet the EU rules for environment, public and animal health, animal welfare, and agricultural practices beneficial for the climate and the environment. Consequently, this helps farmers to implement appropriate solutions for their specific situations, including aspects of climate change adaptation, even if it is not mandatory. Whether to include adaptation advice is up to the Member States (M 2).

- Investments in physical asset (M 4)
- commitments into agri-environment and climate measures (AECMs: M10),
- support for organic farming (M11)

EUROPEAN GREEN DEAL AND CAP 2023-2027 Soils will play an important role in the Green Deal roadmap, linked with the Farm to Fork strategy, Biodiversity strategy (and related EU Soil Strategy for 2030), and climate change (Climate Law).

Under Pillar 1, the newly introduced eco-schemes (agri-environment-climate measures) are required to be implemented, although which measures to offer is up to Member States. Adaptation to climate change and sustainable use of water resources are included as objectives.

Chapter 4

Farmer engagement as key to successful climate adaptation

4.1 Summary

Understanding farmers' perception of the associated risks and opportunities related to climate change and how this may influence their decisions or response strategy is instrumental in defining supporting policies and research. In EJP Soil CLIMASOMA, we look specifically at adaptation measures via soil management and types of cropping systems. This study explores and aims to understand the complexities of farmers' decision making via a systematic literature review.

The willingness to act and adapt to climate change is strongly related to a farmers' awareness and how concerned they are about the impacts and risks of climate change. The key focus of many farmers are their crops and associated yields. Specific soil-related adaptation strategies are often not the most prevalent measures being mentioned by farmers in the context of climate change adaptation. However, in recent years, scientific literature shows that the trend towards including soil health has increased.

Barriers and drivers (e.g., policies, biophysical conditions), as well as farmer's perception of barriers and drivers (e.g., peer pressure, farm risk) determine the willingness of farmers to adapt to climate change. The general barriers and drivers for adoption of climate change adaptation strategies were: awareness of climate change and perception of risks, access to information on climate change & adaptation, social capital, financing, policy/regulations, use and access to technologies. However, whether these factors were a driver or barrier depended on the context of the farmer and their farm. This shows the importance of understanding the context of the farmer, the local and regional specificities, including the social and cultural context. Therefore, understanding the more intricate decision-making related to farmer's barriers and drivers, at farm level, for specific soil climate adaptation measures is an area that needs further research.

Acknowledging the large diversity of farmers, their perceptions and ambitions, across Europe should be the starting point. Grouping farmers based on farm characteristics (e.g., socio economic, farm type) and their personal characteristics (e.g., profit seeking, pro-environment) may help to identify potential underlying factors driving farmers. A typology that reflects the diversity of farmers can contribute to a better understanding of the perceptions, aspirations and motivations of different farmers. And so, guide policy, extension services and research to provide targeted support to the different types of farmers.

4.2 Introduction

The impacts of climate change vary across regions and farming systems in Europe. Changes in growing season and crop phenology result in a northwards expansion of areas suitable for several crops and a decline in areas in the south. Extreme weather events such as heavy showers, droughts and heat waves will impact all parts of Europe (AgriAdapt, 2017; Jacobs et al., 2019; Ciscar et al., 2011). Recent extreme weather events such as the intense rainfall and related flooding during the summer of 2021 were experienced across the Atlantic and Continental parts of Europe. "*Climate change impacts on agriculture is projected to produce up to 1 % average gross domestic product loss by 2050 but with large regional differences*" (Jacobs et al., 2019). Therefore, more support is needed to help farmers adapt to the changing production conditions they are facing.

So far most of the attention in relation to climate change and adaptation of the agricultural sector has focused on soil management and cropping systems (Ewert, 2015; Smith, 2012; Olesen et al., 2011). The farming system approach which links the decision-making process to farm management strategies was highlighted by Meuwissen et al. (2019) and Reidsma et al. (2015). However, farmer's decision making and the role a farmer plays in implementing mitigation and adaptation strategies are often not considered. The importance of taking a broad behavioural perspectives to help improve the legitimacy of soil governance and facilitate better targeted actions to stimulate the adoption of adaptation measures implemented by farmers is gaining increasing recognition (Bartkowski and Bartke, 2018; Bijttebier et al., 2018).

Clearly there is a greater need to start understanding farmers' perception of climate change, its associated risks and opportunities and how this may influence their decisions regarding their adaptation measures in relation to soil management and cropping systems. This study will explore this topic via a systematic review of the literature and combine this with information from relevant EU projects. In this way aiming to gain a better insight into our current understanding of farmers' and the diverse spectrum of:

1. *how farmers are influenced by the perceived risks/opportunities of climate change (CC) and how this affects their management decisions or CC adaptation strategies- including soil management?*
2. *what are the drivers/barriers for CC adaptation measures?*
3. *what are the needs of the farmers for successful adaptation strategies and*
4. *how to engage better with farmers to ensure their resilience against CC through appropriate soil management measures?*

4.3 Methodology and data source

4.3.1 Behavioural paradigms and models

Understanding farmers' motivations and barriers for soil related climate adaptation is complex and there are many behavioural paradigms and models used to understand the decision making process of farmers (Bartkowski and Bartke, 2018; Mills et al., 2017; Mitter et al., 2019). For this study, the behavioural model of Mills et al. (2017) was used, to frame our review of the literature on farmers' drivers and barriers for implementing soil related climate change adaptation. It was developed to better understand farmer's decision making in relation to agri-environmental schemes, a context which is potentially like that of climate change adaptation. According to Mills et al. (2017) "there is a consensus that farming systems are heterogeneous and therefore that the context and outcome for decision-making in relation to the environment will vary greatly spatially. This heterogeneity and context relate to an "intricate interaction of agronomic, cultural, social and psychological factors; and each of these factors plays interwoven roles in each national, regional and specific farm context. These affect the individual farmer's response..".

According to the IPCC climate change adaptation is defined as making "adjustments. in response to actual or expected climatic.. effects or impacts.. (to reduce vulnerabilities)... and to moderate potential damages or to benefit from opportunities associated with climate change" (Smit and Pilifosova, 2003; Cardona et al., 2021). The risk of impacts from climate change events are " determined not only by the climate and weather events (the hazards) but also by the exposure and vulnerability to these hazards" (Cardona et al., 2012). However, effective CC adaptation strategies to manage these climate risks not only depend on the actual potential exposure and vulnerability, but also on how farmers perceive their level of exposure and vulnerability to the effects of climatic events. This is important, as this relates to farmers' behaviour and how concerned a farmer is about CC or how they experience it, as this in turn may determine how they may manage associated risks (risk preference) to their farm and their livelihood.

We used the Mills et al. (2017) behavioural model to help structure the findings of the literature review. It was adapted to the decision-making context of climate change (CC) and the associated decision making of the farmer in relation to CC adaptation (Figure 4.1). The Mills model is at the center and consists of three major components:

1. *Ability*- a farmer's ability to adopt a measure, which relates to the biophysical limitations of the farmers location and their socio-economic situation. Bartkowski and Bartke (2018) refer to this as objective characteristics.
2. *Willingness*- a farmer's willingness to adopt a measure, which relates for example to how a farmer perceives and evaluates a situation (e.g. risks, opportunities, capacities), experiences social pressure to behave in a certain manner, as well as their identity and beliefs. This is the most complex component of Millers behavioural model, for which the theoretical background is rooted in the Theory of Planned Behaviour (Ajzen 1985, 1991) and Value- Belief-Norm theory (Ewert, 2015). Put simply these underpin the behavioural characteristics of the farmer (Bartkowski and Bartke, 2018).
3. *Engagement* - a farmer's engagement with advisors or farmer networks, in other words how developed a farmer's social capital is.

Using the adapted decision making paradigm of Mills et al. (2017) we conducted a review of the literature in relation to European farmers' perception of climate change and adaptation, and its relevance to soil management measures. While not a fully comprehensive systematic review, it is to our knowledge the first to combine only European case studies in order to synthesize the present European farmers' perspective of climate change and how this potentially relates or not to adoption of soil-related adaptation measures.

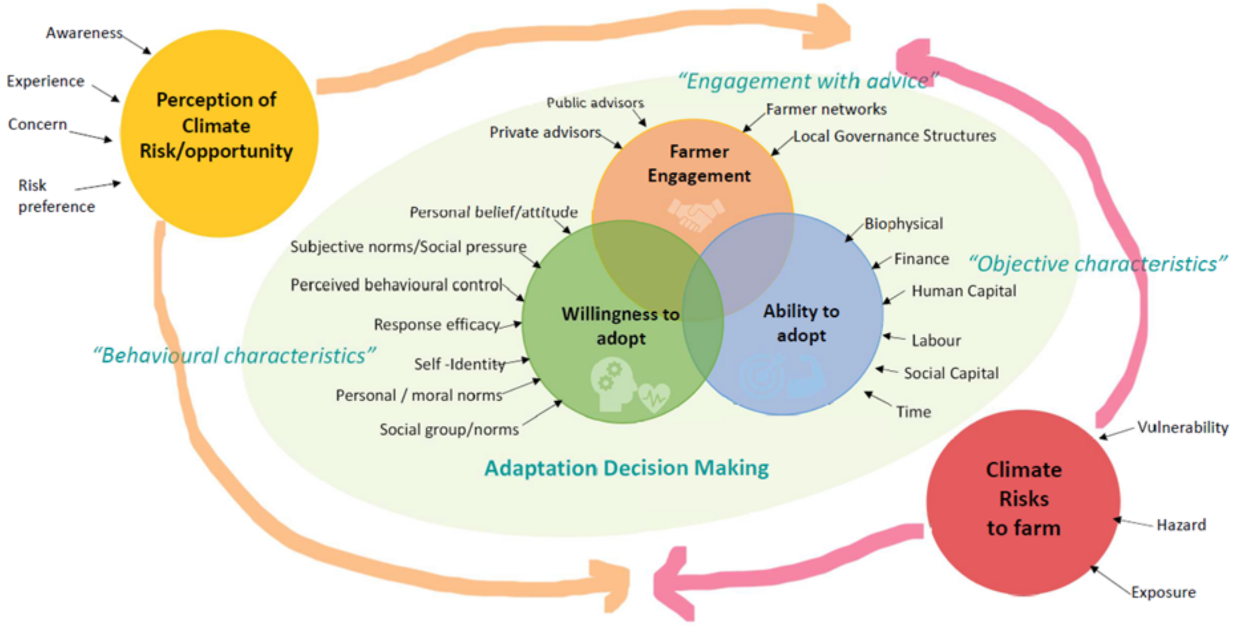


Figure 4.1: Graphical representation of the important components involved in decision making process of farmers for adaptation in the context of climate change. Derived from literature sources: (Mills et al., 2017; Bartkowski and Bartke, 2018; Cardona et al., 2021; Iyer et al., 2020), with and adapted Mills behavioural model at the centre.

4.3.2 Review of Literature

Online search for literature

A review of the literature was carried out using first the search engine Scopus and a later stage Google scholar. We conducted a search focusing only on farmers' perception of climate change in order to obtain papers which also included the themes of farmers' climate change awareness, as well as adaptation. We did not narrow down the focus of the search with a soil search term, in order to gain a greater insight into the broader area of farmers and climate change adaptation.

The following search term was used: TITLE-ABS-KEY (famers AND perception AND climate AND change). This resulted in 1,800 papers being retrieved. Further filtering for European countries resulted in 297 papers remaining. These articles were then further filtered manually based on the following criteria: i) the study took part in an EU country, ii) there was a participatory process involved in the study e.g., group discussions or surveys, iii) the results of the paper were not as a result of a modelling exercise, i.e., with no primary participatory data provided and iv) the paper was in English.

The search was then repeated using the search term: TITLE-ABS-KEY (famers AND perception AND climate AND adaptation) 2. During the manual filtering two participatory studies had an additional paper associated with the study (i.e., two papers per study). These four papers were kept in the study, as the results of the papers differed to justify their inclusion. The additional Google scholar search resulted in one more paper. This resulted in a total of 25 papers to be reviewed, which also provided a broad geographic spread to give an insight into farmers' climate change perceptions and potential adaptation behaviours in the climate risk regions identified across Europe (Figure 4.2). A further additional paper was added to the review after feedback during the CLIMASOMA webinar held on the 24th of September 2021. Thus, making a total of 26 key papers included in the systematic review. An additional paper was used for the assessment of farmer types.

Online search for relevant EU projects

The EU Cordis website and EU Life project database was searched for all relevant EU projects which involved stakeholder participation in the context of climate change and climate change mitigation. It also linked to the work outlined in Chapter 5, Untangling the effect of climatic drivers with space-for-time or manipulation experiments . We opted for this because in many cases the activities relating to farmers' adoption of measures for mitigation and adaption are synergistic. This search led to the identification of several EU projects, of which the data and results could be used to support the context setting of the research outlined in this report regarding climate change risk and the decision making of farmers (Figure 4.1). We focussed on the two most relevant projects.

The EU Life project, Agri-adapt, was used to help provide the climate risk contexts for this study. The results of this project found that there were four major climate risk regions, facing various climate change risks and opportunities Figure 4.2.

The EU FP7 CATCH-C project (EU2020), was used to provide additional insight into farmer's drivers and barriers for adopting two soil related adaptation measures, conservation tillage and cover crops. These measures were selected as they were the most widely adopted throughout the European regions covered in the CATCH-C project.

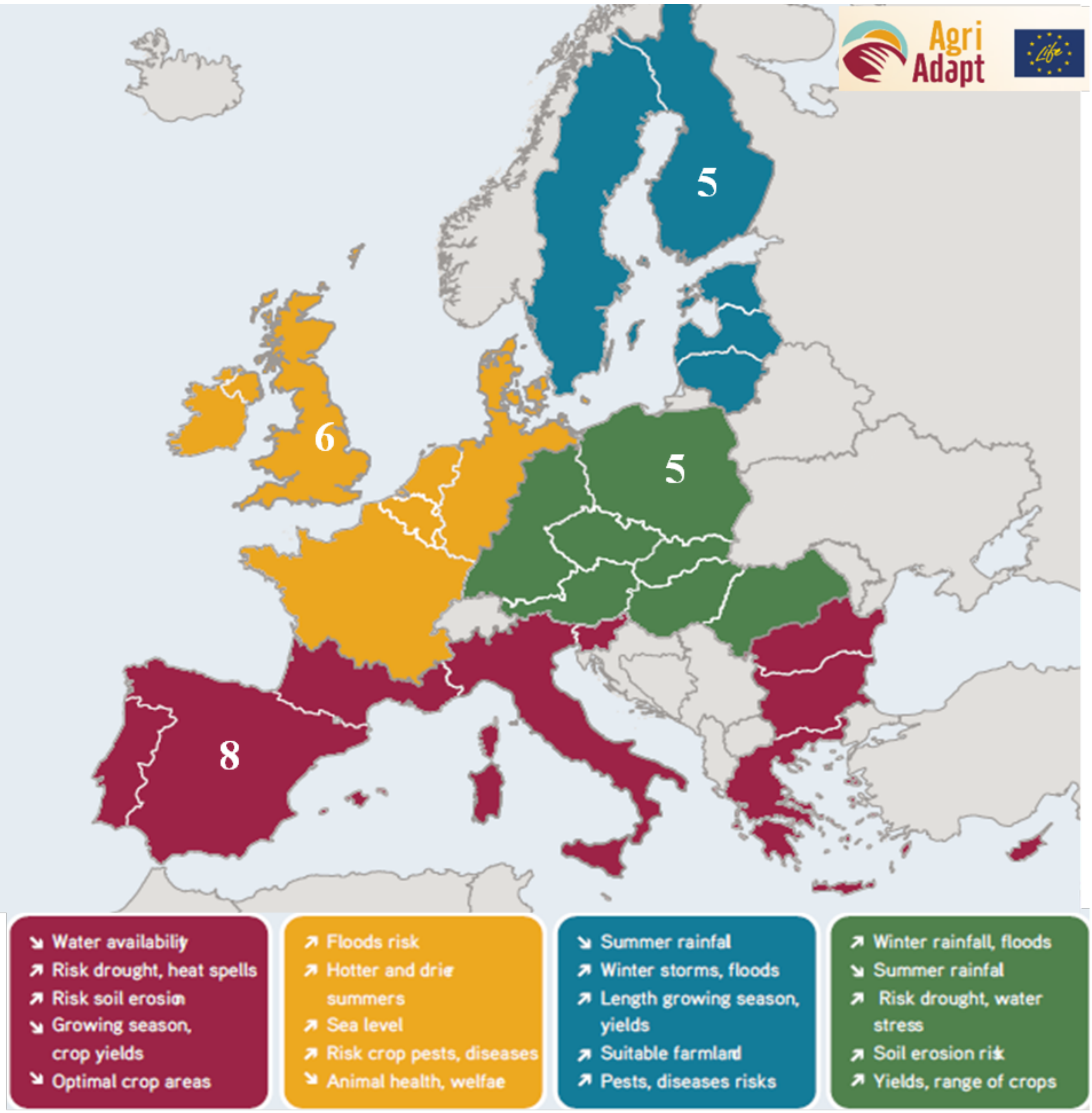


Figure 4.2: Agri Adapt climate risk regions, as well as the list of climate risks and opportunities outlined for each climate risk region. Red – southern climate risk region, yellow-Atlantic risk region, blue – northern climate risk region and green – continental risk region. The numbers refer to the number of papers found in the literature review for each of the climate risk regions. Two papers are not included in the numbers presented in the map, as both papers were studies which included two regions in their study, one paper had the Atlantic/Southern region (France), and one paper had the Atlantic/Continental regions (Germany).

Text mining and analysis

The selected papers were then systematically reviewed for the following aspects outline in Figure 4.3. This was done through manually text mining each paper. To carry out the text mining, associated statements were first extracted from the papers, key words were then identified and looked for within the text. Following this step all other relevant statements were then identified and extracted from the papers' texts.

Table 4.1 provides examples of key words and statements associated with each aspect. The extracted statements were then organised per reviewed paper in an excel sheet according to several pre-defined categories (Supplementary materials Chapter 3). Once extracted, the statements were further analysed for key repeating terms and from this a frequency analysis was carried out.

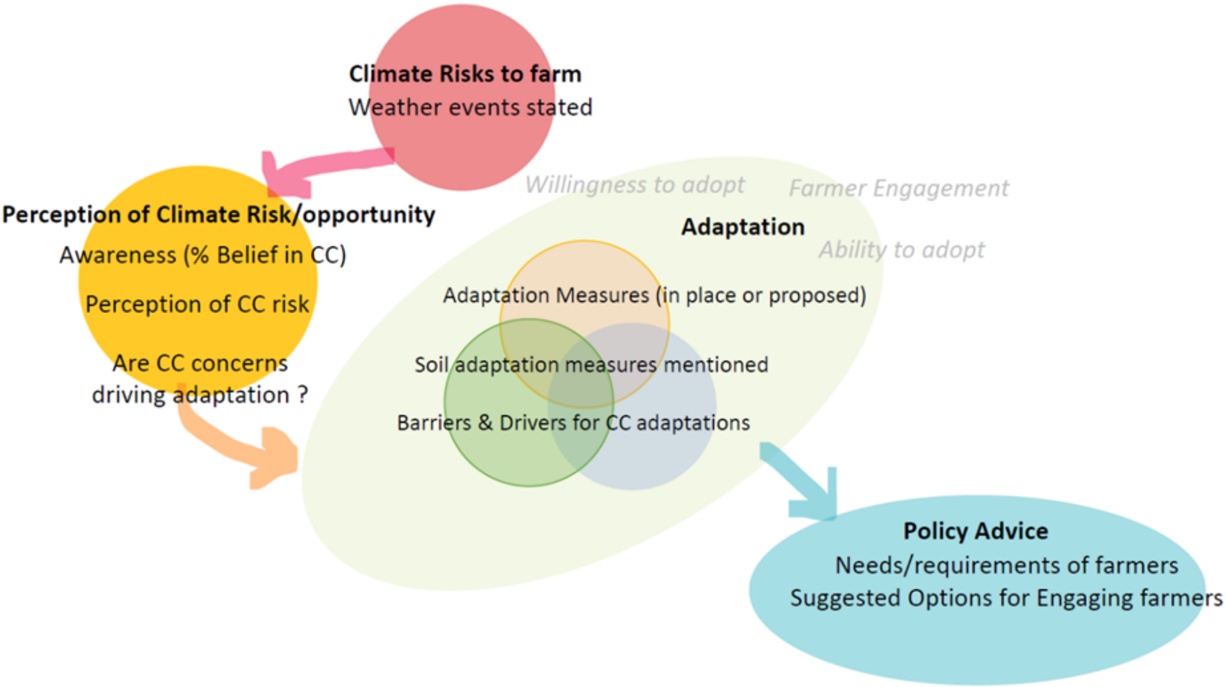


Figure 4.3: Graphical overview of topics systematically reviewed in literature based on the important components for decision making and climate change context as shown in Figure 4.1

In the case of identifying barriers and drivers for farmers, these statements were selected from the papers either because they were explicitly referred to as: drivers or barriers, constraints for the farmers or limiting factors for adoption of adaption measures (Supplementary materials Chapter 3 Annex V). However, in some papers there were very integrated narratives or results of multifactorial statistical analysis provided and, in these cases, it was not always so clear what was a driver or barrier - potentially grey areas - these grey areas were left out here. Farmer's needs were also identified from results and conclusion parts of the articles reviewed, see Table 4.1.

In the review of the literature several articles outlined the concept of identifying "farmer types" to enable an effective and pragmatic engagement with farmers to support them in their process of climate change (CC) adaptation (Pröbstl-Haider et al., 2016; Barnes and Toma, 2012; Hammes et al., 2016; Käyhkö, 2019). These farmer types were analysed and summarised and from this a CC adaptability spectrum was derived based on the descriptions of the farmer types identified in the various studies (see Supplementary materials Chapter 3 Annex VI).

Table 4.1: Summarised examples of statements and key words used for text mining

Aspects	Example key words	Statements	Goal of text mining
Weather events	temperature, drought, storms, hail, rain, flooding, frost, extreme weather events, season	“more extreme weather events (such as hailstorms, spring droughts and downpours)”[1]	To determine the types of weather conditions occurring at the locations of the surveys, the weather conditions the farmers were experiencing or perceiving to experience
Farmer’s CC awareness and perception of risk[2]	perception, awareness, risk	“Smaller farmers are more aware of CC”[3] “less sceptical farmers (are) about climate change were those who had first-hand experience of adverse natural events.”[4]	To determine the potential factors that influence a farmer’s level of cc awareness and understanding of the related cc risks and opportunities.
Adaptation measures[5]	Tillage, cover crop, amendments, mulching, rotation	“of the farmers ..willing to adapt...were ready to use new drought- and pest-resistant crops”.[6]	To determine what the farmers are currently doing or willing to do to reduce their vulnerability to climate change risks
Soil adaptation measures	Soil, soil management, structure, properties	“took up no-till ... to increase soil moisture and soil organic matter content”[7]	To determine, intention of management strategies specifically mentioning benefits to/from soil or soil properties e.g., improve soil water holding capacity, reduce compaction, soil management change, no tillage to improve soil moisture
Barriers and Drivers	Driver, barrier, likelihood to adapt, increase/decrease capabilities, positive/negative effect	“The largest single barrier ...(for) adaptation measures are perceived to be .... policy regulations”[8] “constrained by limited financing”[7]	To identify the barriers and drivers which are leading to farmers adopting CC adaptation strategies
Farmer’s needs	Help, needs, key actions	“most farmers said that it is important to adapt at farm level”	To identify what the farmers are saying as their needs to support their adoption of adaptation approaches

1. Statement taken from Käyhkö (2019)
2. This was a quantitative aspect also.
3. Statements taken from: Jänecke et al. (2016); Nguyen et al. (2016)
4. Statement taken from Nguyen et al. (2016)
5. Adaptation measures identified as part of Chapter 2, Soil and crop management for climate-smart soils
6. Statement from Galdies et al. (2016)
7. Statement from Ibrahim and Johansson (2021)
8. Statement from Woods et al. (2017)
9. Statement from Hovelsrud et al. (2015)

4.4 Results

4.4.1 Perception of climate risks or opportunities

Farmer's Climate change awareness, experiences and perceived risks and opportunities

Table 4.2: Range of percentages reported for climate change awareness of farmers across the four climate risk regions[1,2,3]

	Believe in CC	**Don't Believe in CC**	**Neutral**
Atlantic	47-88	10-18	20-37
Continental	64-85	2-22	4-33
Southern	60-90	10-20	
Northern	22-97	1-52	2

1. Atlantic (n=8), Continental (n=5), Southern (n=6), North (n=2), n refers to no of studies.
2. An additional study was added here (Smit et al. 2019), which also provided insight into three of the different climate risk regions, Atlantic, Southern and Continental
3. Values are rounded to the nearest decimal point

From the literature reviewed, the results indicate that there is a high awareness of climate change across a broad European geographic of farmers (Table 4.2). However, it must be noted here, that these are summarised results combined in a simplified way, as "climate change" was framed differently in different studies e.g., as anthropogenic or natural. This needs to be kept in mind when looking at the absolute results of this table. However, the relative aspects are what should be noted here e.g., higher or lower.

On average approx. 81% of the farmers interviewed recognize some form of climate change, with approx. 8% still rejecting that climate change is happening at all. Of the latter, many believe the extreme weather events they experienced to be either weather anomalies or natural fluctuations of weather (Nguyen et al., 2016; Käyhkö, 2019). When investigated further to determine if farmers perceived CC weather risks to their farm, it was found that a relatively high percentage of farmers interviewed (41-90%) across several countries (Italy, Germany, France, Denmark, Malta and England, n=6) perceived changing weather patterns on their farms to be negative (CC). However, in the study of (Jänecke et al., 2016), some of the farmers interviewed (24%) experienced advantages of weather changes to their farm.

When asked about future or more long-term CC impacts and the effects this may have on them directly, approx. 44% of farmers were unsure or didn't have an opinion, 45% of farmers perceived the CC risks to be negative for them and their farms. However approx. 10% saw CC impacts to be positive (Barnes and Toma, 2012; Sorvali et al., 2021; Tzemi and P. Breen, 2016; Woods et al., 2017; Smit et al., 2019). These positive results were mostly found in the northern Atlantic and northern country regions, reflecting the predicted positive climate change (CC) effects of longer growing seasons and warmer summers (AgriAdapt, 2017).

In many of the studies reviewed, the entry point for farmers discussing climate change was in relation to weather patterns and changing weather or seasonal patterns, we discuss this further in the next section.

Weather events and farmer’s risk perceptions.

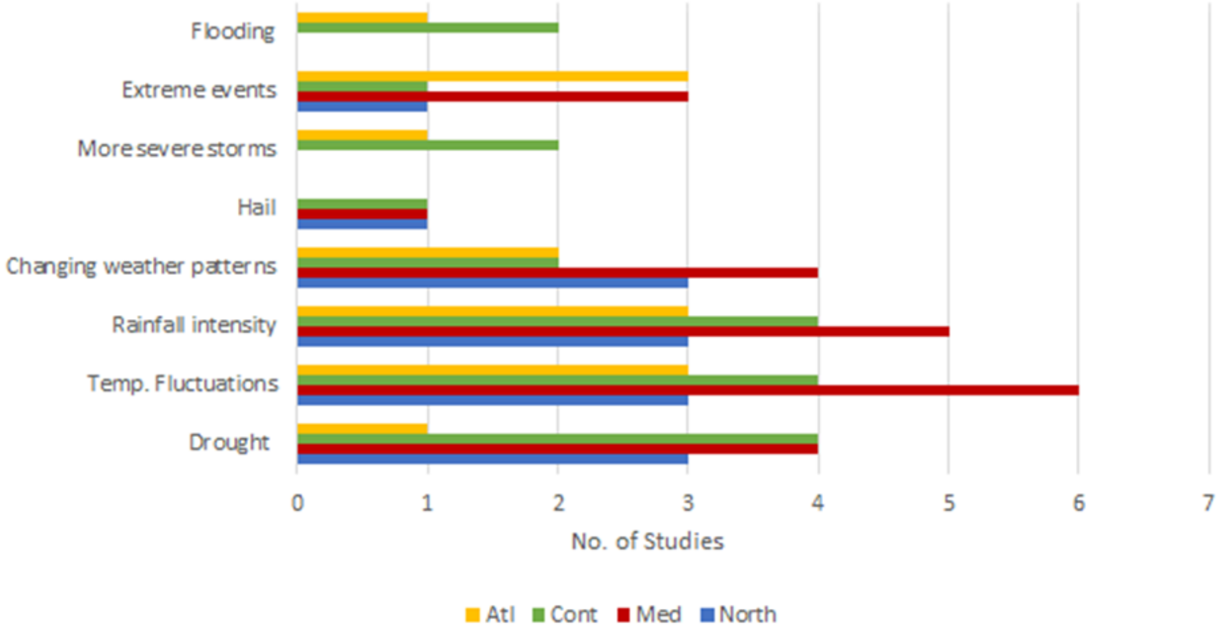


Figure 4.4: Frequency of studies mentioning weather events related to CC hazards

In general, the weather events mentioned in the studies, particularly those relating to farmers concerns, are aligning with the climate change weather events outlined in the EU Life Agri Adapt project (Figure 4.1). Weather is the daily and annual experience of a farmer and in many cases farmers have weather stations on their farms to compare and analyse these short-term fluctuations, whereas climate change is classically measured over decades (Cardona et al., 2021; Hamilton-Webb et al., 2017). The entry point for farmers discussing climate change was weather patterns and changing weather or seasonal patterns (Nguyen et al., 2016; Käyhkö, 2019; Hamilton-Webb et al., 2017). One example of this was outlined by Nguyen et al. (2016), who identified that “increased or decreased temperature patterns are “touchable” phenomena that farmers can personally feel by themselves, whereas rainfall amount is less easily observed and perceived by human senses without appropriate instruments”. Therefore, when farmers perceptions were compared with real regional weather data there were sometimes deviations in what the farmer’s perceived to experience and what had actually occurred (Ibrahim and Johansson, 2021; Graveline and Grémont, 2021; Cohen et al., 2014; Nguyen et al., 2016).

Furthermore, perceptions differed among farmers for interpreting and understanding climate patterns based on their differing contexts and experiences (Jänecke et al., 2016; Nguyen et al., 2016; Eggers et al., 2015). In some cases, differences between farmer perceptions related to the **type of farming system,** for example a dairy farmer will have a different annual calendar of farm tasks when compared to an arable farmer. This means that the weather patterns they are exposed to, expect or experience throughout the year will differ and thus their perception of potential risks will differ too (Cohen et al., 2014; Nguyen et al., 2016).

Another example of differing perspectives among similar farmer groups is the **use of technologies**. Graveline and Grémont (2021) found that the farmers using irrigation technologies were less perceptive to the effects of climate change, such as drought, because their irrigation management mitigated the true impacts of increased drought events.

Further influential factors on a farmer's perception of climate change and the potential consequences were**: age, education, location** and **farm size** (Jänecke et al., 2016; Cohen et al., 2014; Eggers et al., 2015; LI et al., 2017). However, there wasn't always unanimous agreement between these factors or the combination of these factors. One example of this variability is farm size. In some cases farmers with smaller farms were more aware of CC and perceived the risks more strongly (Jänecke et al. (2016)), in other cases it was larger farmers that seemed to be more aware of CC effects (Smith (2012)). For some of these cases the researchers related these differences to the economic situation of the farmer and how dependent the farmer was on their farm income as part of their total income. In other words how vulnerable their income was to the effects of CC (Cohen et al. 2014; Jänecke et al. 2016; Li et al. 2017).

A common observation across many of the studies was that first-hand experience of adverse weather events related to climate change did influence the farmer's perception of risks (Menapace, Colson, and Raffaelli 2015; Nguyen et al. 2016). However, there were also "paradoxical" cases found where farmers believed in CC experienced losses due to weather events which could be attributed to climate change, but did not associate their losses with CC (Jørgensen and Termansen (2016)). In many of these cases farmers failed to make the connection between climate change and the adverse weather events they were experiencing. In other words, they were aware of climate change, but considered it to be something of a global phenomenon, not a local one and therefore, did not perceive it as a risk for their farm or for their livelihood. Furthermore, they perceived these adverse weather events as some sort of variation in the weather (Jørgensen and Termansen, 2016; Hamilton-Webb et al., 2017).

To summarise, these results illustrate how European farmers experience and perceive their risks or opportunities relating to weather events and climate change and how they differ vastly, across a multitude of factors. Many of these factors are interrelated combining characteristic factors (Figure 4.1) of their farm, such as between farming type, location, socio-economic aspects, as well as behavioural characteristics such as, personal attitudes and norms (awareness) in relation to climate change and its potential effects (positive or negative).

But the question is: *'Does this awareness and perception of climate change consequences drive farmers' adaptation behaviour, particularly in relation to soil-related climate adaptation measures.'*

Are climate change concerns driving farmer's adaptation behaviour?

Studies included in the review hypothesized that the psychological distance of climate change (Spence et al. (2012)) should have a large influence on whether farmers have or would implement adaptation strategies to reduce the effects of climate change events (Galdies et al., 2016; Hamilton-Webb et al., 2017). This is where climate change events are more tangible to the farmer, as they have had experience with such events recently, or they have occurred to them personally or in close vicinity to them (geographically), or people in their social network, region or country have experienced them. When these climate events are more real or tangible the result is a greater likelihood that adaptation measure will be put in place. However, the findings from these studies, as well as the results from this review, illustrate that farmer decision making for adaptation is more complex than expected.

Many of the articles reviewed found that farmers who were **both aware of CC, experienced its effects and who were also highly perceptive of the associated risks and opportunities**, were more likely to adopt adaptation strategies on their farms (Merloni et al., 2018; Woods et al., 2017;

Käyhkö, 2019). While, several other studies found the opposite, climate change concern was not the direct cause of farmer's adaptation behaviour (Jørgensen and Termansen, 2016; Hamilton-Webb et al., 2017; LI et al., 2017). In these latter studies, **other socio-economic indicators or farm risk factors appeared to have more influence on the farmers management strategies**. According to Hamilton-Webb et al. (2017), "farmers were most likely to rate climate change as a low risk to business, when presented with other potential threats, such as risk from market price fluctuations, animal disease, changes to agricultural policy and extreme weather". It is important to note here again, that in some cases farmers did not make the connection between extreme weather events and climate change. It is also this lack of connection which can have important ramifications for famers adaptation strategies and for CC policies and communication strategies to address the need for adaptation in the agricultural sector (Hovelsrud et al., 2015; Merloni et al., 2018; Jørgensen and Termansen, 2016; Käyhkö, 2019; LI et al., 2017).

Mitter et al. (2019) summarised the situation very well in their study of Austrian farmers, "most adaptation measures have been or are planned to be implemented due to a mix of climatic and non-climatic reasons...therefore, engagement strategies to strengthen adaptation in agriculture should consider regional peculiarities, farm type-specific needs and challenges, farmers' socio-cognitive processes, and adaptation costs and benefits. Promoting multi-purpose adaptation could be a promising option in order to increase adaptation intention .. among farmers"

Therefore, it is also good to understand in general what kind of adaptation measures farmers are currently implementing on their farm or what they propose to implement on their farms, be that due to climate change alone or a combination of factors, perhaps indirectly related to climate change. We show the overview of adopted adaptation measures in the next section.

4.4.2 Adaptation measures implemented or proposed by farmers

In many of the studies reviewed they found that farmers' preferences for adaptation are simple, flexible and cost-effective measures to their current farming system, rather than larger measures which cannot be easily modified again afterwards (Eggers et al., 2015; Woods et al., 2017). The most prevalent adaptation measures mentioned are presented in Figure 4.5.

The most frequent adaption strategy mentioned relates to modifying cropping management, with crop diversification being the main measure mentioned, followed by drought tolerant crops, cover/catch crops and crop rotations. The latter two measures being important options for soil-related climate adaptation, see Chapter 2, Soil and crop management for climate-smart soils. For the southern regions, drought-tolerant crops were one of the most frequently mentioned adaptation strategies.

Tillage practices are important soil related climate adaptation strategies which a farmer can implement, as it can contribute to increases in organic matter content, as well as having either a positive or negative influence on the physical structure of the soil, which in turn can affect a soil's water holding capacity, soil porosity and erosion potential. Furthermore, soil tillage can influence the soil's biodiversity (e.g., worms) which also in turn can have knock on effects on for example the soil infiltration rates or organic carbon content (for further insights into tillage practices on soil please see Chapter Chapter 2, Soil and crop management for climate-smart soils. The tillage strategies referred to in the paper's reviewed were reduced, minimum and no tillage. These were the

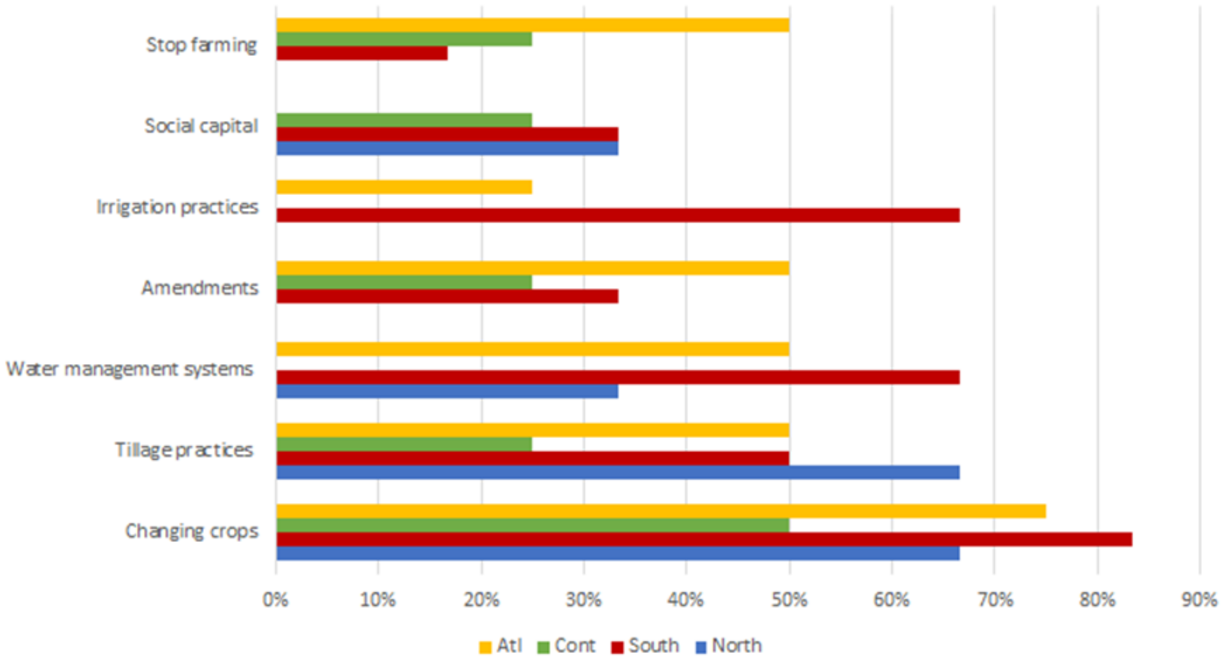


Figure 4.5: Percentage frequency of different adaptation strategies mentioned in the papers reviewed (n=18, not all papers reviewed included adaptation), explanation of terms in text below

descriptions provided, but for many cases no clear indication of plough depth was provided

In terms of amendments, many farmers were looking at strategies to reduce or efficiently use inorganic fertiliser, with one or two of them discussing options of mulching and manure applications, both important for soil related climate adaptation.

Water management system is an aggregated term for the restructuring of (part of) the farm landscape to ensure better water storage or protect from flooding through buffering e.g., using dykes and ditches, water storage reservoirs. These changes to the water resources management are therefore different from irrigation strategies which aimed to improve water use efficiency of crops (i.e., less losses, improved uptake). It can also be seen in Figure 4.5, that these are two very important climate adaptation strategies in the southern regions, those at most risk of severe drought events.

In some studies part of the farmer adaptation strategy was to increase their engagement with extension services, advisors, farmer networks and cooperatives (social capital). In some extreme cases farmers would consider leaving farming entirely if CC risks became too high. They were generally farmers with smaller holdings, lower capital for investing in adaptation strategies and, or had no successor to pass the farm onto (Eggers et al., 2015; Cohen et al., 2014).

However, what is not entirely clear from this overview of adaptation measures is what role soil, or soil health plays in the implementation of adaptation strategies. We look at this in the next section.

4.4.3 CC adaptation measure - specific focus on soil

Nine out of 19 papers (47%) were found to have a direct reference to soil health when exploring adaptation options to climate change, with a greater number of papers in the Northern and Southern regions including soil related adaptation measures. Figure 4.6b, shows that papers including soil-related adaptation measures appeared to increase with time and after 2018 all papers reviewed including some sort of soil-related measures. The management strategies mentioned were a mixture of cropping, tillage and amendments (see Section 4.4.2).

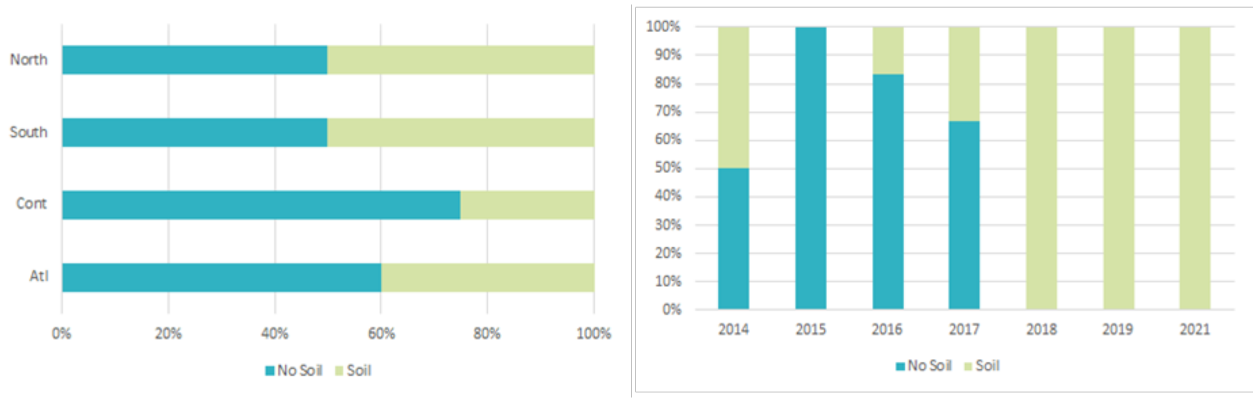


Figure 4.6: Percentage frequency of CC awareness and adaptation strategies mentioned in the papers reviewed that had a direct link to soil structure and health a) grouped according to climate risk regions and b) grouped according to year of publication

Soil structure and soil health was used and incorporated into the studies in a variety of ways. In the study of Jørgensen and Termansen (2016) precipitation events and their effects to soil were used as a proxy for climate change impacts as a means of engaging better with Danish farmers. The study of Eggers et al. (2015) found that soil structure made farmers more aware of climate change. In one of their case study regions in Germany. Farmers working on low-quality soils (higher sand content and limited water holding capacity) and continental climate, had a higher climate change awareness than the farmers in a contrasting Alpine region. This was because they experienced the effects of drought stress much more and made them more vulnerable to the effects of the drought.

In the northern regions, Sorvali et al. (2021) survey of Finnish farmers found that “adaptation measures were seen in the context of good agricultural practices and maintenance of soil conditions”. Furthermore, Ibrahim and Johansson (2021) study received the feedback from farmers on the island of Öland off the coast of Sweden that there was a lack of “advisory support on improving soil quality and conservation agriculture (related to soil management)”.

In some of the papers one of the reasons for inclusion of soil-related climate adaptation measures, was due to its inclusion by the researchers themselves, e.g. as a topic in their surveys or interviews with farmers (Graveline and Grémont, 2021; Jørgensen and Termansen, 2016; Ibrahim and Johansson, 2021; Ronchail et al., 2014). This could have created a bias, as it is unclear if farmers themselves would have brought up this matter. **However, in the general overall context of farmer’s climate change adaptation strategies, from this limited review, soil health was not found to be the main point of entry for European farmers**. This is also supported by the review of Bartkowski and Bartke (2018) who found that “..... *hardly any study had a specific focus on soil management, most ....had only an indirect link to soil....*”. In this study the predominant focus of many of the farmers included in these studies (mainly conventional farmers) was on their crops. This is logical as for many farmers this is their main source of income and what is tangible to the farmer. Crops are also one of the easiest management strategies to adapt e.g., using a newer drought-resistant cultivar instead of a less drought-resistant cultivar (Section 4.4.2).

4.4.4 Farmers' barriers and drivers for adoption of adaptation measures

Barriers and drivers at the farm level

There is a wide variety of interacting factors explaining why farmers either adopted or were willing to adopt certain measures to reduce the impacts of climate change events. The reasons are organised into groups in Figure 4.7. Many of the reasons provided relate to farmers' ability to adopt measures, their willingness to adopt measures (behavioural characteristic of the farmer) and their level of engagement with, e.g., other farmers, farm networks or advisors.

As already pointed out above, the more aware and concerned farmers are about climate change the more likely they are to adopt adaptation measures. Awareness is one of the major drivers for adoption of climate change adaptation measures (Barnes and Toma, 2012; Ibrahim and Johansson, 2021; Woods et al., 2017).

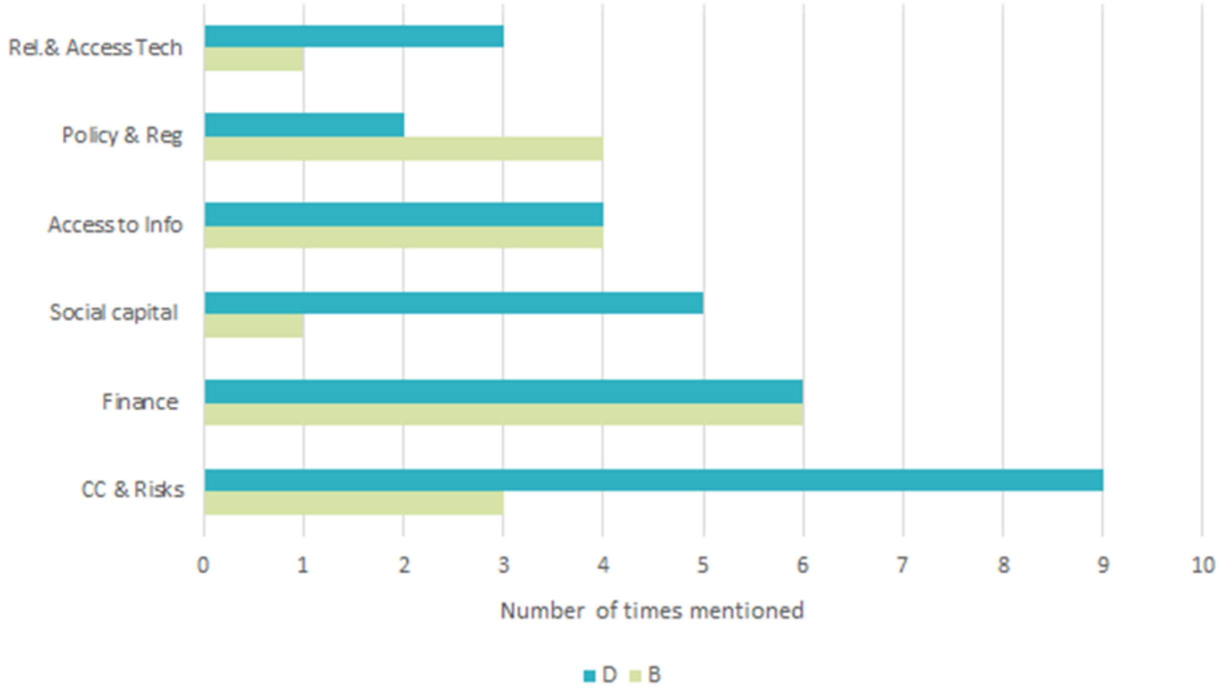


Figure 4.7: Predominant categories of barriers (B) and drivers (D) for farmers in relation to climate change adaptation strategies. Rel & Access Tech = relationship and access to technology, Access to Info = access to CC adaptation information, CC & Risks = awareness of CC and its associated risks, Policy & Reg= Policy and regulations.

Finance, depending on the farmers' context, can either be a barrier or driver for climate adaptation. The contexts that were identified as barriers for adaptation related to farmers concern about sizeable investment costs and returns, ability to access sustainable financial capital, preference for more simple and cost effective solutions, as well as the fear that the “wrong adaptations” might lead to lower market price for their crop (Hammes et al., 2016; Hovelsrud et al., 2015; Cohen et al., 2014; Galdies et al., 2016; Ibrahim and Johansson, 2021; Ronchail et al., 2014). With regards to financial drivers, the contexts related to: dependency on farm income (i.e. the more dependent the more likely they were to adopt changes), financially better off farmers had a greater ability to invest in adaptation strategies and technologies, and farmer’s risk preferences, the more risk averse the more likely they were to adapt (i.e. behavioural decision-making related to climate change concerns) (Merloni et al., 2018; Graveline and Grémont, 2021; Hamilton-Webb et al., 2017).

Another driver found in many of the papers was the social capital, or level of engagement of the farmers, as these connections seemed to increase their adaptability to CC e.g. farmers engaging with other farmers, farmer’s organisations or cooperative (Graveline and Grémont, 2021; Cohen et al., 2014; Nguyen et al., 2016; Li et al., 2017b). However, this was again not always the case. Ibrahim and Johansson 2021 found that some farmers in their study region had a “negative social mindset” and this acted as a barrier for adoption of certain CC measures (e.g., having own machinery not willing to share between them) in the Northern region.

Access to information and support for climate change adaptation was again either a barrier or driver depending on the farmer’s context. Good access to information and opportunities to engage in co-learning or education had a positive impact on CC adaptation (Hovelsrud et al., 2015; Nguyen et al., 2016; Bojovicab et al., 2012; Li et al., 2017b). In cases where the farmers had poor knowledge or were not supported effectively through, for example advisory services, lack of information was a barrier for CC adaptation (Hamilton-Webb et al., 2017; Galdies et al., 2016; Ibrahim and Johansson, 2021). It was common throughout many of the papers, for farmers to state that they would like more information and advice about climate change risks and how to prepare their adaptation strategies better. Furthermore, in many studies the lack of adequate advisory support was found to be a relevant barrier to action. Another aspect mentioned was the need for better weather reports available in a timely fashion to farmers (Nguyen et al., 2016; Bojovicab et al., 2012; Bonzanigo et al., 2015), as this would help the farmer to prepare better for weather events. Policy and regulations again can be a barrier or driver for farmers depending on context and location.

Policies and regulations acting as drivers for farmers are those which provide incentives and financial assistance for CC adaptation, enabling the implementation of certain adaptation measure (e.g. irrigation) (Graveline and Grémont, 2021; Hovelsrud et al., 2015). However, in many contexts policy and regulations were a very relevant barrier for farmers to implement adaptation measures, with some perceiving top-down policies, such as the European Common Agricultural Policy, as being too restrictive and not supporting good adaptation practices. Farmers were concerned that CC adaptations could conflict with cross-compliance rules, resulting in loss of income (Käyhkö, 2019; Ibrahim and Johansson, 2021; Woods et al., 2017).

Many of the Barriers and Drivers found in the CC adaptation literature reviewed are still on a more general farm level combining several technical measures, with none of the studies exploring in detail the barriers or drivers for implementing specific individual soil related adaptation measures. From Section 4.4.1, farmers are implementing adaptation measures on their farms due to a mixture of climatic and non-climatic reasons.

> “Adaptation by any other name. . . is still adaptation” (Woods et al., 2017)

In the next section more detailed descriptions of the barriers and drivers which farmers have in relation to tillage and cover crops is provided from the EU FP7 CATCH-C project (Supplementary materials Chapter 3 Annex III). These are two of the most important soil adaptation measures (Chapter 2, Soil and crop management for climate-smart soils).

Barriers and Drivers for specific technical measure - Tillage(CATCH-C project)

Adoption and behaviour of farmers towards non-inversion tillage and no- tillage was studied in 19 European Farm Type Zones (FTZs) across all eight countries participating in CATCH-C. The results were generated from a survey consisting of approx. 2,500 farmers (please see Supplementary materials Chapter 3-Annex III for better understanding of FTZs and the CATCH-C project).

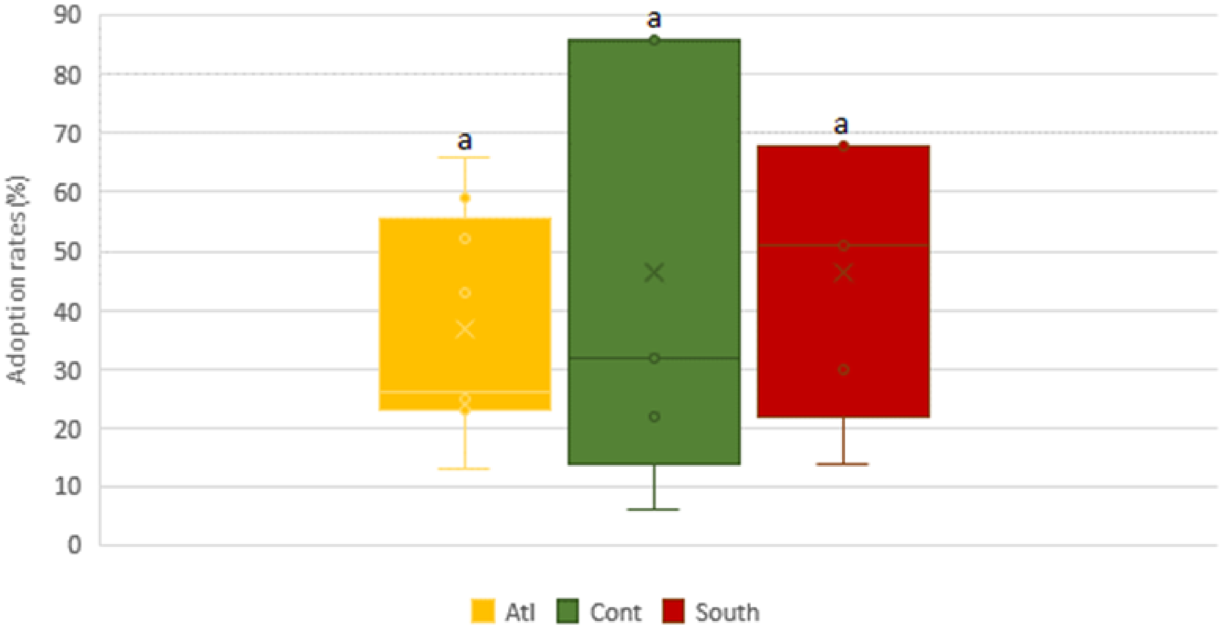


Figure 4.8: Range of adoption rates for conservation tillage for the CATCH-C FTZs grouped according to the climate risk regions of this study: (Atl) Atlantic (13-66%), (Con) Continental (6-86) and Southern (14-68%). Different letters denote significant difference on a level of p<0.05, Anova p=0.46.

Figure 4.8 shows the adoption rates for the climate risk regions included in CATCH-C, with a bigger range of adoption observed for the FTZs (see Supplementary materials Chapter 3-Annex III) found in the continental region, than the other two climate risk region – Atlantic and Southern. In general, they found that adoption rates of non-inversion tillage and no-tillage was much lower on dairy farms than on arable farms, as to be expected since tillage plays less of a role in dairy (with mostly grassland that is not generally tilled). They also found that there was a high variability in adoption rate among (the 19) FTZs, however within countries, this adoption rate seemed to differ less. The top three types of barriers and drivers that farmers provided for these differing adoption rates across the different FTZs can be seen in Figure 4.9.

From Figure 4.9 the major driver for adopting conservation tillage or no tillage practices for farmers are the multiple benefits to soil health. The reasons provided by farmers ranged from improving soil structure and soil life to increases in soil organic matter and prevention of soil erosion. The top three drivers (Figure 4.9) to enhance the willingness of farmers to adopt conservation tillage

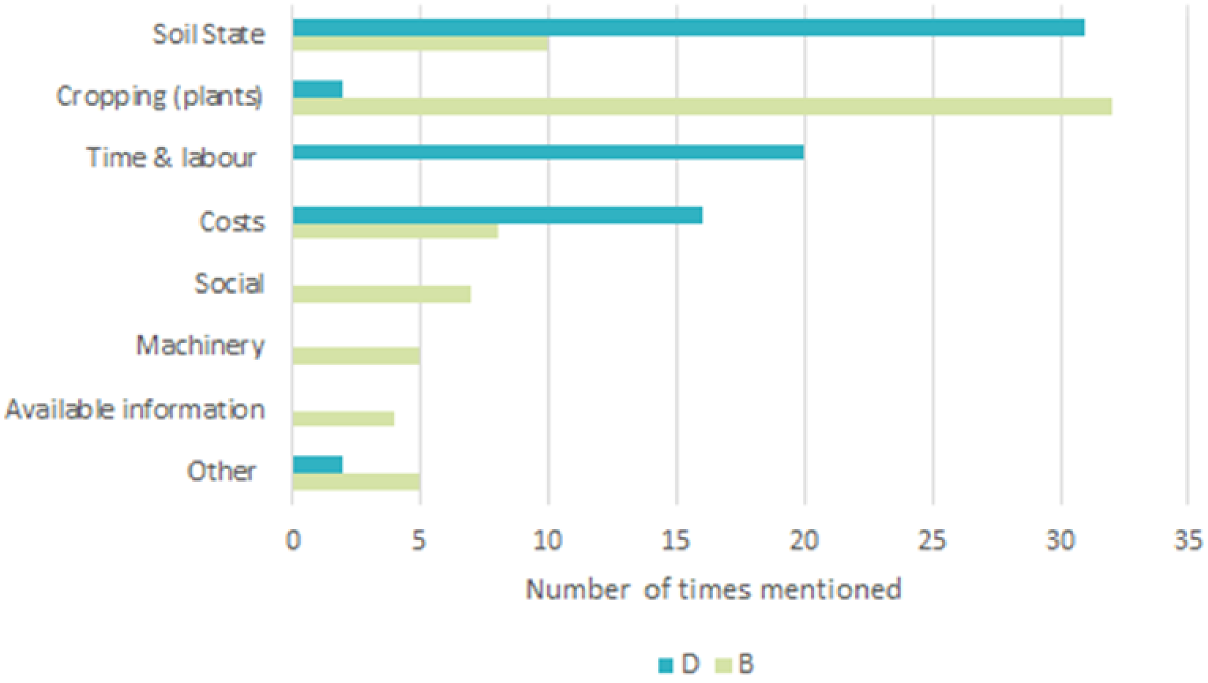


Figure 4.9: Frequency analysis to summarise the top three drivers and barriers for all farmers for adopting and implementing conservation tillage measures on their farms, aggregated to topics. (Data taken from the report of (Pronk et al. 2015), Table 10 and Table 11) . D = Driver and B= Barrier. Soil state refers here to soil properties and condition of soil.

were determined to be related to the attitudes of the farmers – their personal belief of what could or should happen if conservation tillage would be implemented (Figure 4.1). The CATCH-C study also showed that farmer's attitudes towards the different tillage practices varied across the various FTZs.

The greatest barrier for adopting conservation tillage related to crop production and the risk of greater pressure from weeds, as well as the knock-on effect of an increased need to use crop protection measures (financial) according to the farmers. In some cases, farmers also indicated the state of their soil (soil state) as a barrier. With some farmers believing that the use of conservation tillage could reduce soil water retention or accentuate water logging, while other farmers stated as a reason that their soils are heterogeneous. The top three barriers reducing farmers willingness to adopt conservation tillage were, therefore, determined to be a mixture of attitude and perceived behavioral control with some subjective norm (Figure 4.1). A perceived behavioural control is defined as the perception of how easy or difficult it would be to adopt conservation tillage. A subjective norm is the perceived social pressure, a sort of peer pressure to do something. The CATCH-C project showed that the decision making of farmers resulting in their non- adoption of the different tillage types could be quite a complex matter.

Only a brief select summary is provided here of the CATCH-C survey details, for more information on these results please see the CATCH-C reports and peer reviewed articles (Supplementary materials Chapter 3-Annex III). Another adaptation measure studied in more detail in the CATCH-C project is the use of cover crops. We discuss this next.

Barriers and Drivers for specific technical measure -Cover crops (CATCH-C project)

The adoption rates for the use of cover crops in the different climate risk regions included in the CATCH-C project are shown in Figure 4.10. Adoption rates in the southern climate risk regions were significantly lower than in the other two regions. Country was found to be an important factor in explaining variation in adoption rate among different FTZs, with no striking differences among farming types (e.g., dairy or arable). The country difference could in some cases be related to legal obligations for including cover crops in a rotation. For example, Dutch farmers have a legal obligation to grow cover crops after maize cultivation on sandy and loess soils.They found that farmers across the European FTZs were in agreement with the scientific evidence that cover crops are beneficial for their soils. The top three types of barriers and drivers that farmers provided for these differing adoption rates across the different FTZs can be seen in Figure 4.11.

It is clear from Figure 4.11 that one of the major drivers for growing cover crops relates to improving the state of the soil (e.g., structure, soil organic matter), lower erosion risk, reduce nutrient leaching. The top three drivers to enhance the willingness of farmers to adopt cover crops were determined to be again related to the attitudes of the farmers (Figure 4.1). The CATCH-C study also showed that farmer's attitudes towards cover crops again varied across the various FTZs.

The reasons provided as barriers for growing cover crops are more varied across the various FTZs than the drivers, even within countries. The major barrier is the additional (financial) cost required for such operations (e.g., fuel, seeds). Social barriers were also found to be very important, particularly in the southern regions, for example, where family and other farmers were provided as reasons for non-adoption. The top three barriers reducing farmers willingness to adopt cover crops were therefore, determined to be a mixture of attitude and perceived behavioural control with some subjective norm (Figure 4.10).

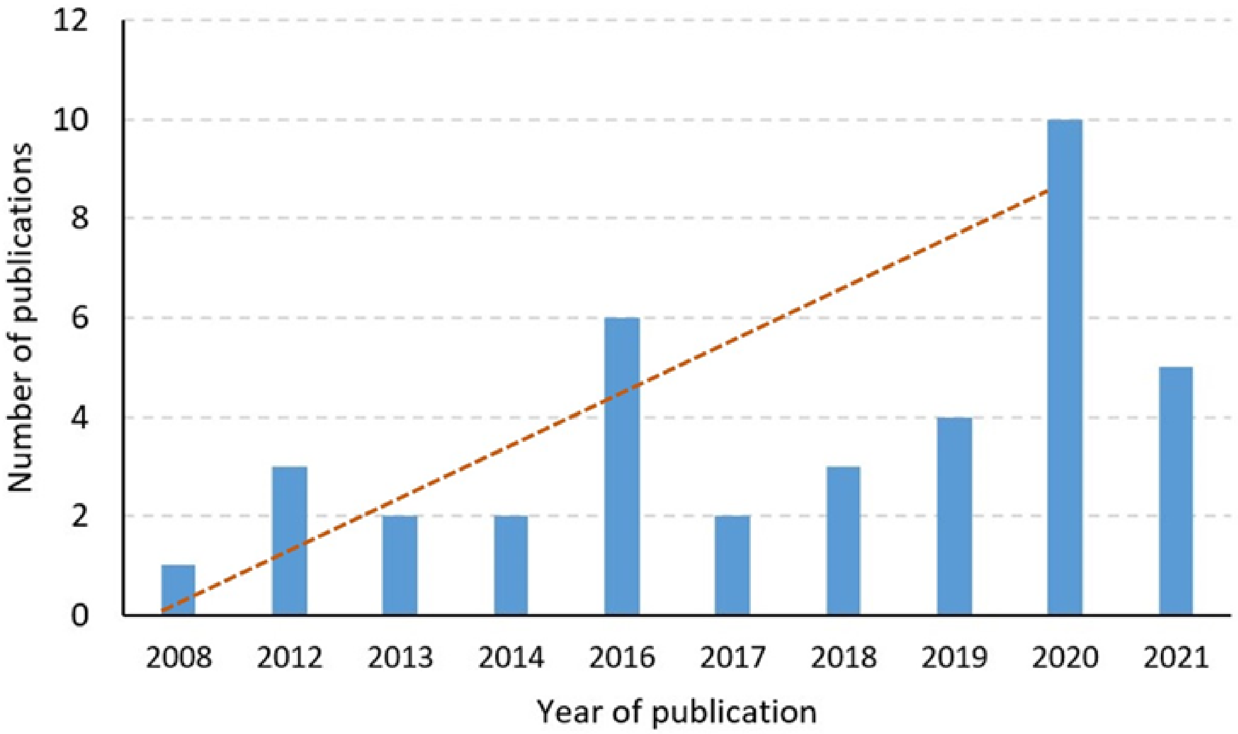


Figure 4.10: Range of adoption rates for cover crops for the CATCH-C FTZs grouped according to the climate risk regions included in this study; (Atl) Atlantic (14-95%), (Con) Continental (42-100%) and Southern (1-55%). Different letters denote significant difference on a level of $p<0.05$, anova $p=0.004$, followed by holm corrected pairwise t-test.

"In general, farmer's social environment stimulates farmers to sow cover crops, except for France. Farmers in Belgium, the Netherlands, Italy and Poland feel stimulated by extension services, not only because extension services are positive towards sowing cover crops, but also because farmers seem to add much value to the opinion of the extension services. An exception are the Italian dairy farmers who feel discouraged by the feed advisors to sow cover crops. In the Netherlands, farmers perceive the positive opinion of literature and study clubs as important drivers" - Pronk et al. (2015)

The results of the EU FP7 CATCH-C project outlined here shows the large diversity of farmer types across Europe, as well as the diverse set of reasoning they have for either adopting or not adopting soil-related adaptation measures such as conservation tillage or cover crops. What they also show is that farmers are very much aware of the benefits to soil that both measures can provide, but despite this, there are still significant barriers which result in their non-adoption of these measures. The lack of willingness to adopt these measures comes from a very broad spectrum of behavioural reasoning, from perception of social pressures, (e.g., other farmers aren't doing it) to the perception that implementing such soil adaptation measures would not be easy because it would be more costly, take more time, or cause yield loss or soil damage. In other cases, the reasons related more to the ability of the farmer, relating to the properties or state of their soil (e.g., high clay content, too heterogeneous), lack of finance for machinery, not enough labour resources to carry out such tasks. In several cases it was a combination of all the three components of Mills et al. (2017) behavioural model: willingness, ability and engagement.

Within the climate adaptation literature reviewed for this study (Supplementary materials Chapter 3-Annex IV), it was not possible to deduct the intricacies of farmers decision making behaviour regarding specific adaptation measures and in particular soil-related adaptation measures. There-

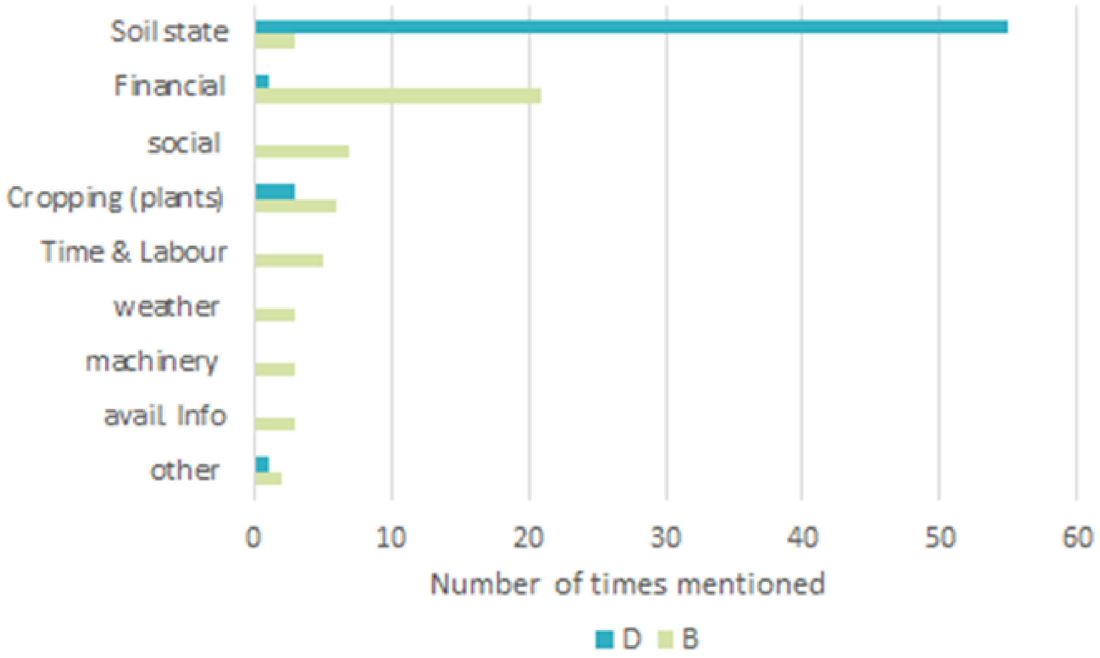


Figure 4.11: Frequency analysis summarising the top three drivers (D) and barriers (B) for all farmers for adopting and implementing cover crops on their farms, aggregated to topics. (Data Pronk et al. (2015), Table 6). (avail info= available information). Soil state refers here to soil properties and condition of soil.

fore, this is an area that needs further research to understand the level of climate change concern a farmer may need in order to overcome their perceived or actual barriers for implementing specific soil-related adaptation measures. However, literature research is only the starting point for meeting some of the farmers needs to support their adaptation. These needs are discussed in the next section.

4.4.5 Farmer's needs to support adaptation

Climate change adaptation is defined as making "adjustments.. in response to actual or expected climatic.. effects or impacts.. (to reduce vulnerabilities)... and to moderate potential damages or to benefit from opportunities associated with climate change" (Smit and Pilifosova, 2003; Cardona et al., 2012). It is clear that there is a large variability in European farmer's adaptation strategies to climate change risks or opportunities. **Soil management strategies are not the main entry-point for farmers dealing with climate change adaptation.** In general, it is rather crops, as this is where farmers see their income affected.

For effective climate change adaptation policies to be developed, it is not only important to understand the potential impact of hazards (climate events), vulnerability and exposure on the objective aspects of a farmer's business (e.g. infrastructures, fields, income), but it is also **imperative to understand how farmer's themselves, experience, perceive and interpret these CC risks**, as this plays a strong role in a farmer's adaptation behaviour and decision making (Merloni et al., 2018; Hamilton-Webb et al., 2017; Galdies et al., 2016; Woods et al., 2017; Sulewski et al., 2020; Hyland et al., 2015; Menapace et al., 2015). Therefore, "Acknowledging farmers' attitudes and beliefs ...(is) an important component in understanding the responsiveness of the agricultural sector...(and) improve the robustness of agricultural systems to climate change" (Jørgensen and Termansen, 2016). The need for understanding the diverse decision-making processes of European farmers can also be seen in the review of the EU Horizon CATCH-C project, as although the farmers were aware of all the benefits of adapting their soil management, they still decided against implementation (Section 4.4.4). Indeed, one of the key recommendations of the CATCH-C project was the need to **prioritise soil adaptation strategy goals more locally**.

Furthermore, "...**communication needs to.. emphasize the connection between climate change and extreme weather events** to allow for farmers to perceive climate change as a relevant and locally salient phenomenon, and subsequent tailored information and advice should be offered to clearly illustrate the best means of on-farm response" (Hamilton-Webb et al., 2017) Part of this improved communication strategies could be to encourage greater involvement in farmer social networks, as social learning has been recognised as a very important means to enhance knowledge and adaptive capacities of farmers (Nguyen et al. (2016)). This was also a key recommendation of the Life Agri Adapt project. Another way is greater interaction with technical advisors, but perhaps in a more "hands- on" manner in field days and open days where farmers can see the practical advantages of certain management changes (Menapace et al. (2015)).

It was also shown that the more concerned a farmer is with climate change risks and opportunities, the more likely they will adapt. Nevertheless, the decisive factors for driving adaptation relate to other, more tangible risks (e.g., market prices, pest and disease). Thus, mixtures of both non-climatic and climatic reasons are leading farmers to change the management strategies on their farms (Barnes and Toma, 2012; Mitter et al., 2019; Käyhkö, 2019; Merloni et al., 2018). Mitter et al. suggested that the best way could be to promote "multi-purpose adaptation strategies" in order to increase adaptation intention even within groups that might be sceptical of CC and its effects on their farm business. However, **engagement strategies need to consider the context specificities and needs of the farm (e.g., region, farm type), as well as type of farmer** and their unique socio-cognitive processes that lead to CC adaptative decision making. Indeed, several studies promoted the use of "farmer types" to "enable the effective transfer and exchange of knowledge which can encourage.. adoption of adaptation and mitigation measures" (Hyland et al. (2015)). We discuss this in the next section.

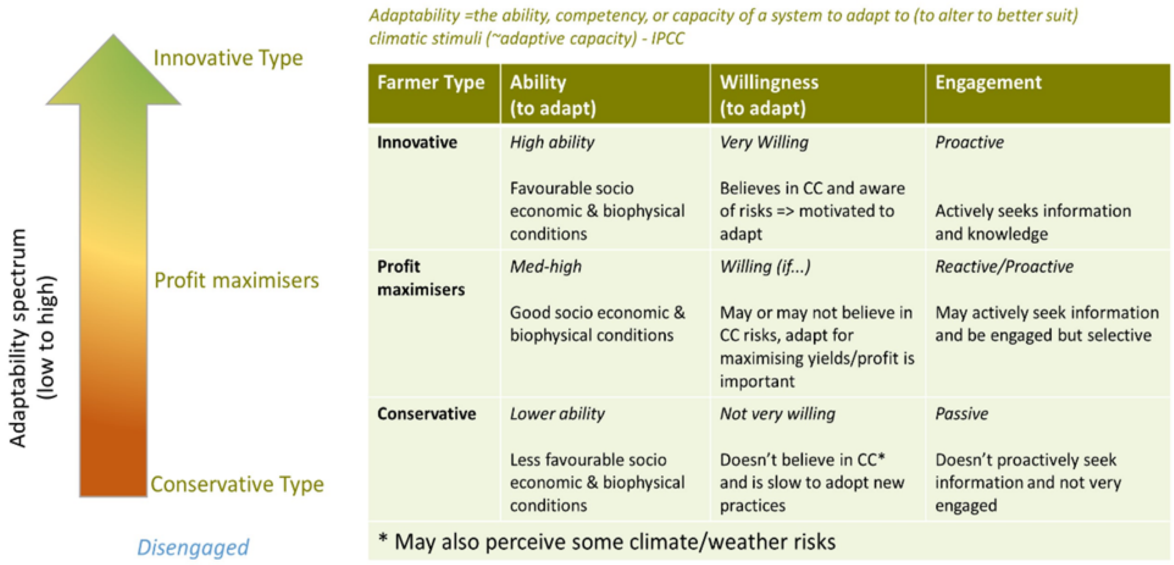
4.4.6 Suggested options for better farmer engagement – Farmer Types

According to the IPCC "Climate adaptability is defined as "the ability, competency or capacity to adapt to (to alter, to better suit) climatic stimuli " (Smit et al., 2001). Figure 4.12 presents the spectrum of farmer types identified in the literature in combination with the summarised descriptions of their adaptability potential, organised according to the important components involved in decision making outlined by Mills et al. (2017). From the literature two extreme farmer types could be identified. These were "the innovative type" and "conservative type", as well as one farmer type who more than likely is found somewhere in the middle of these two. The latter falls into the "maximiser type" – a farmer type whose decision-making process is driven primarily by increasing yields or financial gains (Supplementary materials Chapter 3-Annex VI).

While this is a very broad generalisation, it is still a useful thinking process to help structure the complexities involved in trying to understand the diverse spectrum of farmers and factors influencing their decision making in the context of climate change adaptation. The main reason being that these different farmer types will have differing level of responsiveness to different modes of engagement and communication, e.g., education and training, adopting technologies, increasing their social networks. Conservative farmers are more passive in their behaviour, are less informed about CC adaptation measures and need a more pro-active approach to change their behaviour. For maximisers, information about the economic or yield benefits of CC adaptation measures could be effective. Innovative farmers are already actively seeking for information and involved in networks. Connecting these networks to each other and greater knowledge resources (e.g., research) can stimulate them towards further adaptation measures.

Furthermore, within different regions and farming systems, there will be a large variety of types. However, the ends of the spectrum correspond to what we found in our literature review: those with a higher adaptability (innovative type) and those with a lower (conservative type). Barnes and Toma (2012) identified another type, namely the "disengaged farmer". This is a farmer who essentially has no clear motivational characteristics and seems to be impartial to many environmental and cc adaptation strategies.

Identifying and determining "farmer types" is an area that requires further research, particularly in relation to trying to motivate farmers to implement soil-related climate change adaptation strategies. Here the collection of primary data in combination with agent-based modelling can be a way to analyse the behaviour of different types of farmers.



Adaptability =the ability, competency, or capacity of a system to adapt to (to alter to better suit) climatic stimuli (~adaptive capacity) - IPCC

Farmer Type	Ability (to adapt)	Willingness (to adapt)	Engagement
Innovative	*High ability* Favourable socio economic & biophysical conditions	*Very Willing* Believes in CC and aware of risks => motivated to adapt	*Proactive* Actively seeks information and knowledge
Profit maximisers	*Med-high* Good socio economic & biophysical conditions	*Willing (if...)* May or may not believe in CC risks, adapt for maximising yields/profit is important	*Reactive/Proactive* May actively seek information and be engaged but selective
Conservative	*Lower ability* Less favourable socio economic & biophysical conditions	*Not very willing* Doesn't believe in CC* and is slow to adopt new practices	*Passive* Doesn't proactively seek information and not very engaged

* May also perceive some climate/weather risks

Figure 4.12: Schematic to represent the potential spectrum of farmers adaptability and the" farmer types" that could be associated with the extreme ends of the spectrum and in the middle, as well as their description organised according to the decision-making component of Mills et al. (2017).

4.5 Limitations of the study

Most studies have been conducted in the last 6-7 years and therefore, provide potentially good insight into farmers awareness and perceptions of climate change. However, after the experiences across Europe of extreme climate events (e.g., floods and fires) in the summer of 2021, the climate change awareness and perception of risk have increased. Therefore, the current willingness of farmers to adopt climate change adaptation measures including soil may have altered and a different behavioural landscape may now exist.

The increasing volume of data being gathered as part of the various EU projects, for example, the EU LIFE GREAT LIFE project, EU H2020 Best4Soil project, EU LIFE SOIL4LIFE project might provide even greater insight into European farmers climate change adaptation behaviours and should be further explored. Nevertheless, to our knowledge, there is still only limited data available to provide the necessary insight into the complex interactions between farm and farmer characteristics, climatic region and soil related climate adaptation measures.

4.6 Conclusions

The results of this literature review indicate that the more aware and concerned a farmer is about the impacts and risks of climate change, the more likely he will adopt an adaptation strategy. However, for many farmers adaptation was not purely based on the perception of climate change risks alone. Their decisions are based on both climatic and non-climatic reasons. Therefore, more effective engagement strategies to encourage soil-related adaptation measures should consider 'multi-purpose' frameworks that cover the many areas of risk and opportunities that a farmer faces. Furthermore, soil-related adaptation strategies are not always the most prevalent measures being mentioned by farmers in the context of climate change adaptation. In many cases it appeared that the focus for farmers was on adaptations for supporting their crops and yields. However, in recent years there is a trend, in scientific literature at least, towards also including soil health as a target.

Within the climate adaptation literature reviewed for this study, it was not possible to deduct the intricacies of farmers decision-making behaviour regarding drivers and barriers for specific soil-related adaptation measures. This is because many of the barriers and drivers identified in the papers were based on a more general farm level, which investigates several interacting issues across several specific management measures. The barriers and drivers for adoption of adaptation strategies were found to be: awareness of climate change and perception of risks, access to information on climate change & adaptation, social capital, financing, policy/regulations, and relationship and access to technologies. However, whether these factors were a driver or barrier depended on the context of the farmer and their farm. Thus, showing the importance of understanding the context of the farmers being approached, the local and regional peculiarities, as well as social and cultural issues that may be of importance. This was also the overall finding of the EU Horizon Catch-C project, which illustrated the large diversity of farmers across Europe, as well as the diverse set of reasoning they have for either adopting or not adopting soil-related adaptation measures such as conservation tillage or cover crops. Therefore, understanding the more intricate decision-making, related to farmer's barrier and drivers, at farm level for adopting different soil management measures as climate change adaptations is an area that needs further research.

The development of farmer types is a useful approach to try and understand better the complexities of farmer decision-making. Grouping farmers in a particular location, based on objective characteristics of their farm (e.g., socio economic, farm type) in combination with their personal characteristics (e.g., profit seeking, pro-environment) may help to identify potential underlying factors driving farmers climate change adaptation decision-making. However, the development and use of such 'farmer types' requires further research to determine if it is a good means of assessing farmers potential climate change adaptability.

Awareness and perception of the associated climate change risks prove to be amongst the strongest drivers for climate change adaptation. Therefore, communication of climate change strategies needs to emphasize the connection between extreme weather events and climate change to enhance farmers understanding of the risks or opportunities that the changing climate poses for them. Such a communication strategy needs to be in language that farmers can relate to and understand. One example would be to explain climate change through weather events they experience. It is also important for soil-related adaptation strategies to be more context-specific and to communicate the benefits that soil management can bring about in the context of the extreme weather events they are experiencing directly.

Climate change adaptation takes place at the farm level. Therefore, strategies for CC adaptation strategies need to be designed for farmers at the farm level, and include the relevant information tailored to the weather events or patterns (climate effects) that that farmers are experiencing or can expect to experience. Such a tailored approach needs to engage directly with farmers to understand their barriers and drivers for climate change adaptation strategies. Through such a two-way dialogue process, the appropriate supports can be identified and potentially brought about to encourage adaptations in their farm management, including soil adaptation measures.

One of the barriers for adopting climate change adaptation strategies was lack of information or access to information on how specifically farmers need to adapt to changing climate. Therefore, there is a need to continue to enhance and build the empirical knowledge of soil management options under climatic stresses and make this available in a comprehensive and applicable way for advisors and farmers. There is also a potential for co-learning exchanges between soil scientists and farmers, through for example multi-stakeholder platforms or living labs.

Further additional needs for supporting the climate adaptation of farmers and the agricultural system are outlined in the summaries of the Life Agri Adapt project (Supplementary materials Chapter 3 Annex II) and EU Horizon CATCH-C project (Supplementary materials Chapter 3 Annex III)

Chapter 5

Untangling the effect of climatic drivers with space-for-time or manipulation experiments

5.1 Summary

Human-induced climate change will most likely continue to alter the frequency and magnitude of extreme climatic events in the near-future. It is expected that changes in air temperature (warming) and precipitation regimes will strongly influence soil properties and soil hydrological and biological functioning, while an increase of atmospheric carbon dioxide (CO_2) concentration will mainly affect the photosynthetic efficiency of cultivated crops. Soil processes and functioning are of critical importance for the agricultural sector in terms of plant development and food production. Therefore, a range of soil physical (e.g., structure, porosity, water infiltration, and available water), chemical (e.g., soil organic matter), and biological properties (e.g., soil respiration, microbial biomass C and N, microbial diversity, and enzyme activity) have been identified as potential key soil indicators to understand the resilience and adaptative capability of soils to climate change in both short- and long-term. The findings will provide useful information to understand the main biotic and abiotic factors that influence soil and ecosystems health. In this context, field experiments evaluating the adaptative response of different soils to climate change represent a crucial instrument. Generally, in this type of experiments one or more climatic drivers are altered as single- or multi-factor, while all other variables do not change between the different group of treatments. In this synthesis, **manipulation field experiments**, **space-for-time substitution** approach, **lysimeter**, **ecotron**, and **integrated novel approach** experiments investigating single- or multi-factorial effects of climate drivers (e.g., warming and extended drought) and elevated atmospheric CO_2 on soil properties and functioning were considered. Particularly, **manipulation experiments**, **ecotron** and **lysimeter research** monitor one or more processes and properties in the soil-plant system, following artificial alteration of either precipitation, temperature or partial pressure of pCO_2 regimes. Conversely, s**pace-for-time substitution** soil properties and processes are studied at large spatial scales encompassing a wide range of climates. This synthesis resumes the state of the art of knowledge and knowledge gaps on impacts of changing climatic drivers on soil properties and functioning and adaptation of soil variables to climate change. This report aims at synthesizing and integrating scientific information and evidence on existing studies in order to qualitatively assess the individual or combined effects of climate drivers on soil properties and functioning, mainly related to water infiltration and availability, nutrients availability, soil organic carbon, enzyme activity, and microbial biomass.

The peer-reviewed literature that we have selected to compile this synthesis has been published over 14-years, from 2008 to 2021. The interest of scientific community to better understand the response of terrestrial ecosystems and soils to climate change has increased over the past decade. A total of 39 unique peer-reviewed literature articles were included in this report. Most of the peer-reviewed literature, selected for this report, refers to original research paper, followed by synthesis and review, and meta-analysis. Particularly, the selected peer-reviewed literature focused on studies and observations referring to different scales from national to global, with a greater concentration of data collected in field experiments carried out in Europe, worldwide, or at local level in one Country outside Europe.

Most authors agree that field **manipulation experiments** are powerful tools to understand the resilience and adaptative response of soils to face climate change because they allow to clarify the cause-and-effect relationships in both short- and long-term. Soil response to climatic extremes such as drought events is currently studied worldwide in a growing number of field experiments that predominantly use rain-out shelters. The **space-for-time substitution** approach is an indirect method used for investigating the effects of climatic variation on soil properties and functioning. Particularly, climatic time-series collected in a multiple-site gradient area allow to simulate climate change scenarios current climate to altered temperature and precipitation regimes such as warming, droughts, and floods. **Lysimeter experiments** measure water budget, C and N cycling in the unsaturated and saturated zone of the entire soil profile. Frequently, they are used to quantify the impacts of climate variables on the soil–plant system. Econtron experiments are designed to realistically simulate above- and below-ground environmental conditions by automatically measuring ecosystem processes.

It is well-known that altered precipitation conditions affects both soil abiotic (e.g., water availability, infiltration, and runoff) and biotic (e.g., microbial community and enzyme activity) processes. Regarding abiotic process, long-term increase of water inputs, used to simulate altered precipitation regime, affects soil hydraulic property, by substantially reducing infiltration rates and influencing water retention, especially during dry summer, that can negatively affect microbial abundance and activity. Considering biotic processes, also below-ground C and N cycling are highly influenced by changes in precipitation regimes. Particularly, an increase in precipitation regime may accelerate soil organic matter decomposition, while drought events may reduce the decomposition due to the increased physical protection of soil organic matter. Conversely, bacterial, and fungal communities are relatively resistant to decreased precipitation. Some manipulation experiments, investigating the combined effects of climatic drivers and enhanced atmospheric CO_2 concentration on soil properties, highlight that they directly influence soil water and microbial processes linked to soil organic matter decomposition.

This synthesis covers more than 30 soil variables, such as soil GHG emission, soil water content and hydraulic properties, C and N cycling, meso-fauna (e.g., earthworms and nematodes), microbial community (e.g., fungal and bacteria), and enzyme activity. On the other hand, 7 and 15 publications specifically investigated the individual effect of altered temperature and precipitation, respectively, while the combined effect of climate variables (i.e., “CO_2 + T”, “CO_2 + P + T”, or “P + T”) were investigated in 16 publications.

In general, this synthesis provides a clear overview of the current knowledge on the adaptative response of key soil properties and functioning to climate change based on field approaches. The report advanced our understanding on the impact of climate drivers and enhanced CO_2 concentration on soil properties and functioning mainly related to grassland land use. Therefore, more insights need to be obtained for other land use and soil management practices. This is of crucial importance to help us understand the complex mechanisms underlying the responses of soil system to climate change that are still not completely known.

5.2 Introduction

5.2.1 Aim of this synthesis

Understanding **the direct impact of climate change on soil properties** (e.g., soil structure, porosity, and organic matter stock) **and functions** (e.g., water infiltration and storage) are crucial for identifying research needs to advise practitioners and policymakers. Nevertheless, climate change is a slow process, many of whose effects are only seen at very long time-scales. Adapting to these changes requires knowledge of ecosystem functioning in the expected novel environments through field experimentation and modelling.

To date, many **manipulation experiments** have been carried out in which one or more processes and properties in the soil-plant system are monitored following artificial alteration of either precipitation, temperature or partial pressure of carbon dioxide (pCO_2) regimes. **Space-for-time substitution (SFT)** is an alternative approach, whereby properties and processes are studied at very large spatial scales encompassing a wide range of climates. Also, papers adopting **a gradient design approach** will be examined. Finally, we assessed **ecotron and lysimeter research** results of studies investigating the impacts of climatic drivers (altered temperature and precipitation regimes) and pCO_2 (i.e., enhanced concentration) on soil hydrological and biological functioning. Apart from synthetizing knowledge on direct impacts of climatic drivers on soil properties and functions, this chapter also highlights challenges and opportunities of the different types of experiments analysed in this study.

5.2.2 Background

Increasing greenhouse gas (GHG) emissions are expected to raise global mean temperature by the end of this century (IPCC, 2021). Temperature and precipitation are key climate drivers that affect ecosystem processes (Wu et al., 2011) , with strong ecological implications (Kreyling et al., 2017). Thus, climate change is expected to drive soil and ecosystem variables by directly altering the equilibria of soil processes and by indirectly influencing soil physical structure and biota. Particularly, changes of air temperature (warming) and shifts in precipitation regimes (e.g., amount, intensity, and frequency) have vigorous impacts on soil biogeochemical and hydrological cycles (Gelybó et al., 2018), while the increase of atmospheric carbon dioxide (CO_2) levels mainly affects the crops photosynthetic efficiency (Tubiello et al., 2007). The specificity and magnitude of external abiotic and biotic impacts strongly influence terrestrial carbon (C) balance (Wu et al. (2011) and the adaptability of soils (Gelybó et al., 2018; Tóth, 2008) . Soil types, land use, and management are differently sensitive to climate change depending on their properties and functioning. Understanding the sensitivity of terrestrial C balance to climate change is a high priority, because of the potential of soils for C storage (Cox et al., 2000). It is well-known that soils represent the third largest reservoir of C on the Earth - after oceans and carbonate rocks – and plays a key role in terrestrial ecosystems (Zhang et al., 2008). It is estimated that soil carbon stocks account for 2500 Gt, which include about 1550 Gt of soil organic carbon (SOC) and 950 Gt of soil inorganic carbon (Lal et al., 2007). In European regions, soil types are highly vulnerable to SOC loss, with western and eastern parts of the EU considered at high risk, while soils in southern parts have complex pattern of regions with low and high risks of SOC loss (Stolbovoy et al., 2008). These changes are also influenced by other abiotic factors such as soil texture and water content. As stated by Ćirić et al. (2017), heavy textured, deep (*Vertisols*), and calcareous soils (*Chernozems*), generally rich in SOC and well-structured are less sensitive to weather extremes compared to the shallow (*Umbrisols*) soils, with coarse texture (*Arenosols*) and poorly aggregated, generally characterized by low SOC (*Fluvisols*, *Cambisols*) and affected by water (*Gleysols*, *Gleyic Chernozems*). A range of soil physical, chemical and biological properties are highlighted as potential key soil indicators in relation to climate change. Determining response of soils to climate change based on different soil types and land use management provides useful information on potential soil degradation in the future and might be used as a guideline for soil protection (Ćirić et al., 2017). In this context, soil covered by natural vegetation are lesser affected by projected climate change compared to the soils under intensive agricultural management. Thus, land use and management changes such as conversion from arable to grasslands or increasing crop diversity are expected to limit soil degradation. Figure 5.1 shows a schematic representation of the potential links among climate change, agricultural soil management, and soil properties.

A range of soil properties and functions identifies the status of soils and their relevance to climate change drivers (Table 5.1). The soil physical properties listed in Table 5.1 provide information related to soil structure, porosity, water infiltration, and available water, while the soil chemical and biological properties mainly affected by climate change are related to SOM, soil respiration (Rs), microbial biomass C and N (MBC and MBN), microbial diversity, and enzyme activity. The frequency of their inclusion within a minimum data set were also provided. The selection of these key indicators can be useful to assess the effect of climate change on soil properties and functions, as well as the adaptive capability of soils and their resilience to climate change in both short- and long-term.

Aggregate stability and porosity are determined by soil structure and are related to the resistance of soil aggregates to external drivers such as high intensity precipitation and soil tillage management. Since these processes are related to other soil physical (e.g., water infiltration and storage), chemical, and biological properties (e.g., SOC and microbial activity), they are considered useful indicators to identify the most suitable soil adaptation strategies, especially in those areas where high and intense precipitation are likely to occur (Allen et al., 2011).

Infiltration refers to the rate at which water enters the soil surface and moves through soil depth (Allen et al., 2011). Soil water infiltration is controlled by other soil physical properties (e.g., porosity, field capacity, macropore flow, and texture) and it is considered an important soil property that regulates leaching, runoff, and water availability for plant growth (Franzluebbers, 2002a; Jarvis, 2007). In this context, water availability and water distribution into soil are key processes highly influenced by extreme events (e.g., high intensity precipitation or drought) and soil management strategies (Allen et al., 2011). For instance, the adoption of management strategies that maintain or even enhance water infiltration and storage in soil (e.g., conservation tillage, planting of cover crops, and incorporation of organic matter) may help to mitigate the negative impacts of extreme events (e.g., severe precipitation or drought), limiting the risk of erosion (Lal et al., 2007; Sanchis et al., 2008).

It has been widely acknowledged that SOM is one of the most complex and heterogeneous components of soils because it is composed by an extensive range of living and non-living materials. SOM supports most of the soil processes (Franzluebbers, 2002b), associated with soil fertility, physical stability, and biological activities (Karmakar et al., 2016). It is influenced by external drivers (e.g., climate and land management) and it can act both as a source and a sink of C in terrestrial ecosystems, thus potentially mitigating or accelerating the greenhouse gas (GHG) emission effects (Karmakar et al., 2016). In this context, a decrease of SOM can negatively influence soil quality and health,

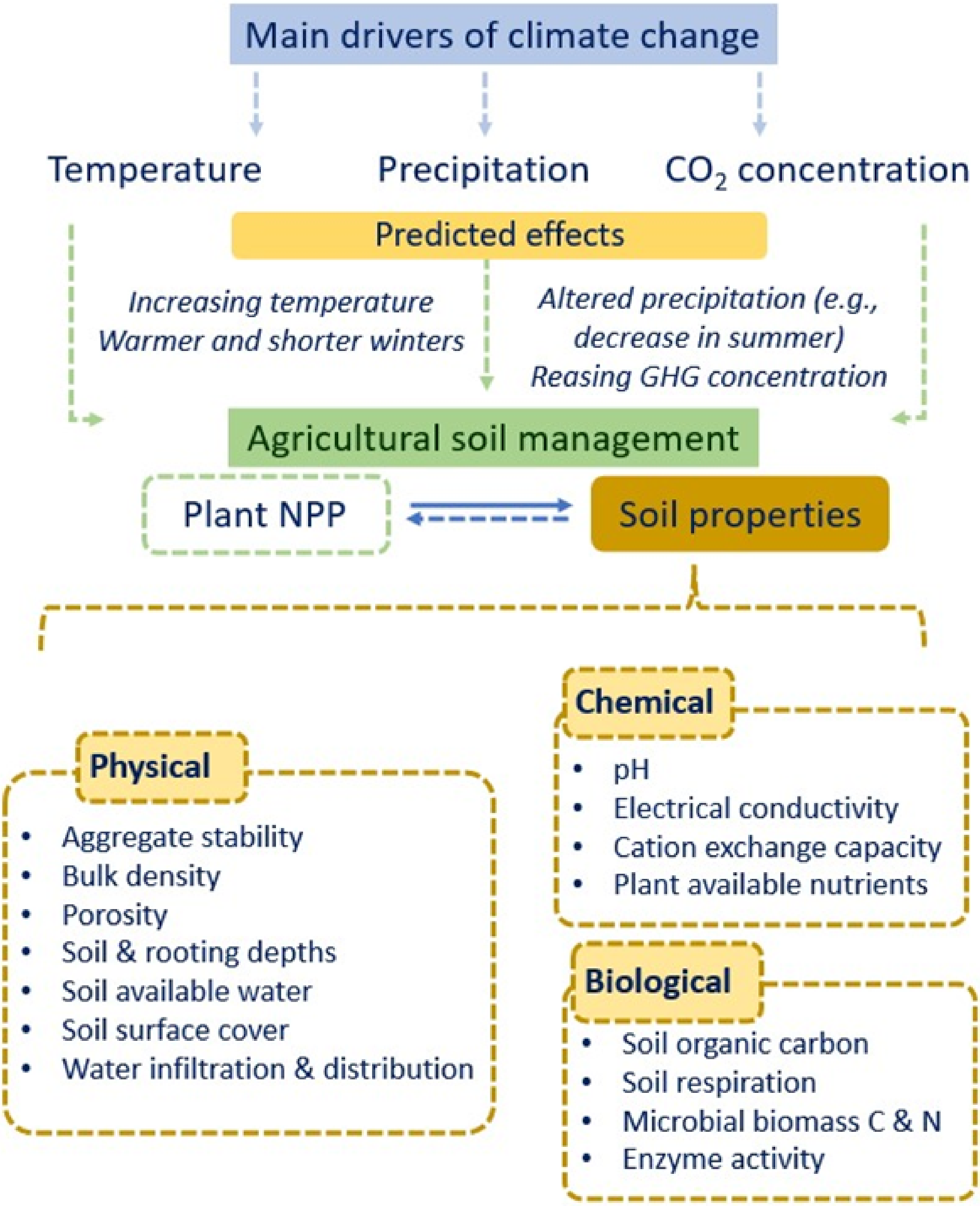


Figure 5.1: *Schematic representation of the potential links among climate change, agricultural soil management, and soil properties (adapted from* Nuttall (2007) *and* Allen et al. (2011)*).*

Table 5.1: Summary of key soil property and function measured or estimated from pedotransfer functions, that are directly or indirectly affected by climate change (adapted from Allen et al. (2011)).

Compartment	Soil property	Soil function	Relevance[1]	Note
Physical	Structure	• Aggregate stability • Organic matter turnover	High	This parameter is frequently included in minimum dataset It gives information on: • Aggregation, surface seal • Indication of water and chemical retention • Transportation
Physical	Porosity	• Air capacity • Field capacity	High	This parameter is occasionally included in minimum dataset It gives information on: • Aggregation in soil surface • Soil crusting that affected aeration and water entry
Physical	Infiltration	• Water availability • Water movement	High	This parameter is occasionally included in minimum dataset It influences: • Soil leaching • Soil erosion
Physical	Soil/plant available water	• Field capacity • Permanent wilting point • Macropore flow • Texture	High	This parameter is frequently included in minimum dataset It gives information on: • Water and chemical retention • Water transportation
Chemical	SOM (light fraction or macro-organic matter)	• Plant residue decomposition • Organic matter storage and quality • Macroaggregate formation	High	This parameter is frequently included in minimum dataset It gives information on: • Loss of organic matter • Soil aggregate formation • SOC • Soil respiration rate • Nutrient supply
Biological	Soil respiration and microbial biomass C and N	• Microbial activity	High	This parameter is frequently/occasionally included in minimum dataset It gives information on: • Soil structure • Nutrient supply
Biological	Microbial diversity and enzyme activity	• Nutrient cycling and availability	High	This parameter is occasionally included in minimum dataset It gives information on: • Biochemical activity • Nutrient supply

[1] Relevance to climate change

by reducing soil structure, water holding capacity, and biodiversity, and increasing the risk of soil erosion and compaction (Allen et al., 2011; Karmakar et al., 2016) .

Rs soil microbial biomass, and enzyme activity are positively correlated with SOM content, and they can easily detect short-term variations in soil processes. Rs is a key biological indicator for soil health, and it can be determined as either CO_2 production or O_2 consumption (e.g., soil or basal respiration). It is widely acknowledged that Rs, soil microbial biomass, and enzyme activity are highly responsive to changes in temperature and seasonal precipitation regimes, which are predicted to change according to global and regional climate models (Allen et al., 2011).

5.2.3 Main objectives

This report aims at synthesizing and integrating scientific information and evidence from peer-reviewed literature on existing field manipulated experiments and SFT substitution studies in order to provide a general overview of the responses of (agricultural) soils to climate change by qualitatively assessing the individual or combined effects of enhanced atmospheric CO_2 concentration and climate drivers such as warming, droughts, and floods on soil properties (physical, chemical, and biological) and functioning. Particularly, aspects related to soil available water, water infiltration, plant available nutrients, soil organic carbon (SOC), microbial biomass and diversity, and enzyme activity are examined.

The specific objectives of the report are to:

- Identify the most important knowledge and knowledge gaps on the relationship between predictive climate change and adaptation strategies of agricultural soils. Here the knowledge gap refers to insights not yet or fully available, generally caused by a lack of essential data.
- Provide recommendations and propose future research directions to integrate manipulation field experiments, SFT substitution approach, lysimeter studies, and ecotron experiments, using a multidisciplinary approach.

5.3 Methodology

In February/March 2021, a brainstorming exercise was carried out to identify potential keywords related to climate and soil. In agreement with the CLIMASOMA project consortium, the most important keywords were identified and selected to be used as search string for collecting relevant published literature. For climate drivers, the selected keywords mainly focused on air temperature, drought, flood, change in precipitation intensity, and climate aggressiveness, while for soil properties and functioning to soil organic matter (SOM), SOC, microbial activity, water storage, and water infiltration. This report was compiled by CREA (Italy) in collaboration with EV-ILVO (Flanders, Belgium) and SLU (Sweden). Figure 5.2 shows the general overview of plan activities used to identify keywords and to collect, process, and extract relevant information from the selected peer-reviewed literature, useful to compile this synthesis report.

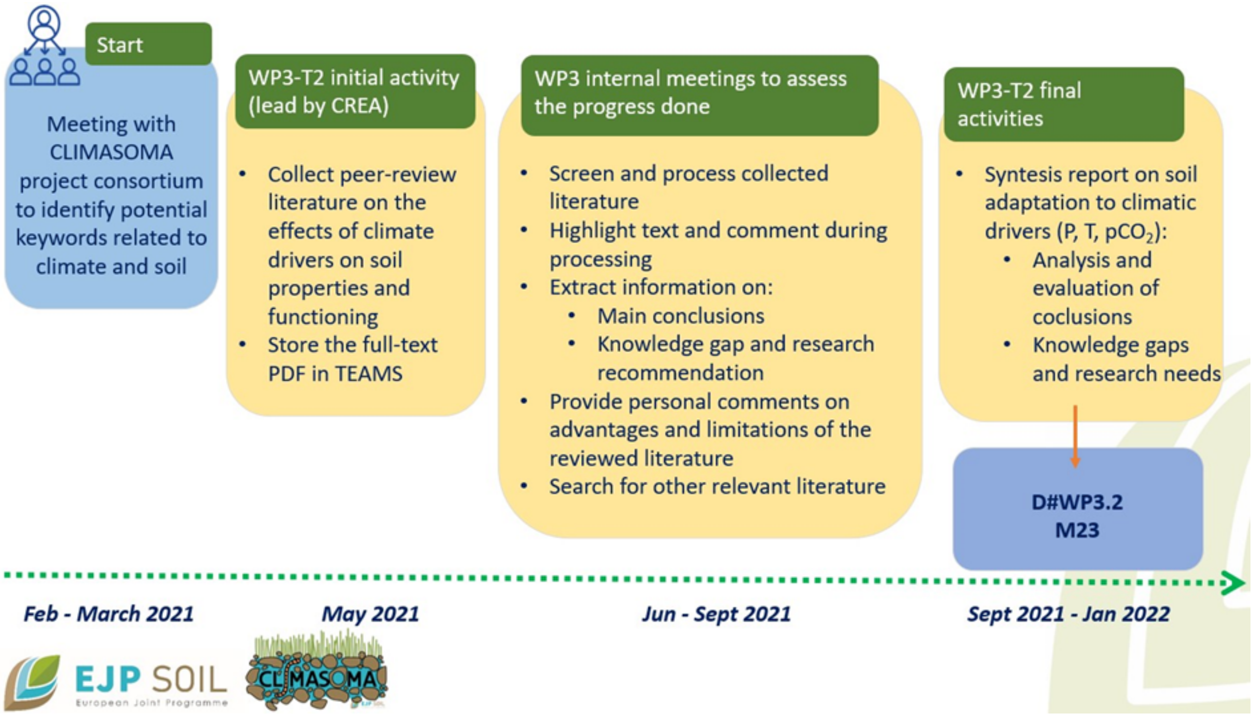


Figure 5.2: Overview of plan activities used to identify keywords and to collect, process, and extract relevant information from peer-reviewed literature, useful to compile the synthesis report.

5.3.1 Literature review methodology

From May to October 2021, we conducted a literature search to collect the published peer-reviewed scientific articles about the individual or combined effects of climate drivers (i.e., decreased and/or increased temperature and precipitation) and enhanced CO_2 concentration on soil chemical, biological, and hydrological functioning. Only scientific peer-reviewed literature written in English and published until October 2021 was included in our analysis. Here, publications different from scientific articles such as books, book chapters, theses, congress proceedings, and other grey literature written in English or in other languages of the CLIMASOMA project consortium were excluded because the accessibility and efforts to collect them overpassed our ability to manage this information. The engines consulted to search the literature were Scopus, ISI Web of Science, and Google Scholar. For qualitatively assessing the single- or multiple-factor effects of climate change on soil properties and functioning, the following combination of search terms were used:

- Temperature: “altered temperature”, OR “increased temperature”, OR “warming”, OR “climate change”
- Precipitation: “altered precipitation”, OR “precipitation addition/removal”, OR “increased/decreased precipitation”, OR “rainfall addition/removal”, OR “increased/decreased rainfall”, OR “drought”, OR “water addition/reduction”
- Atmospheric CO_2 concentration: “elevated CO_2”, OR “increased CO_2”, OR “CO_2 fertilization effects”
- Soil linked water and physical terms: “available water”, OR “water retention”, OR “hydraulic conductivity”, OR “moisture”, OR “infiltration”, OR “aggregate stability”, OR “aggregation”

- Soil linked chemical and biological terms: “organic matter”, OR “degradation, OR “stress”, OR “respiration” OR “CO_2” OR “carbon” OR “nitro” OR “N_2O” OR “CH_4” OR “GHG”, OR “microb” OR “enzyme” OR “bacteria” OR “fungi”, OR “faunal”
- Ecosystem type and land use system: “grassland”, OR “cropland”, OR “meadow”, OR “peatland”, OR “tundra”, OR “agricultural system”, OR “mixed”, NOT “urban”
- Type of field experiments: “manipul”, OR “space-for-time substitution approach”, OR “gradient design”, OR “lysimeter”, OR “ecotron”.

Generally, the dataset of the selected literature covered a limited range of land use, ecosystems, types, and biomes, mostly oriented to grassland or semi-natural systems. Specifically, only few studies were focused on agricultural land and cropping systems (e.g., Poll et al. (2013a)). Therefore, to enlarge our understanding on the effects of climate drivers on soil variables, meta-analysis, synthesis and review, encompassing a wide range of soil characteristics such as soil C and N cycling, microbial communities, enzyme activity, and soil physical properties were also considered.

For inclusion into the synthesis, the original research papers, meta-analysis, synthesis and review had to meet the following criteria:

- They had to refer to field studies where the magnitude of climate drivers was manipulated or a SFT approach was used in order to compare the effects of current and future climate on the soil response variable(s);
- they needed to study the effect of at least one climate variable, including atmospheric CO_2 concentration increase, temperature or precipitation changes;
- they needed to contain at least one response variable from the following list: microbial community, C and N cycling, SOC change, soil respiration, water storage;
- they had to be relevant for European agriculture and environmental zones.

Applying the above-mentioned criteria, 39 studies were found suitable for this synthesis.

5.4 Results and discussion

A total of 39 unique peer-reviewed literature articles (Table 5.2) were included in this report. Most of the peer-reviewed literature, selected and analysed in this report, refers to original research paper (76.9%), followed by synthesis and review (20.5%), and meta-analysis (2.5%), as reported in Table 5.2.

The peer-reviewed literature that we have selected to compile this synthesis has been published over 14-years, from 2008 to 2021. Figure 5.3 shows the number of peer-reviewed scientific articles published per year that has been included in this report. A total of 8 selected papers (20.5%) have been published in the first period (from 2008 to 2014), while the other 79.5% in the second period (from 2015 to 2021). The year 2016 presented a peak (*n*=6), 2020 reached the highest number of publications (*n*=10), and 2021 had another peak (*n*=5), although the data for this year was incomplete as our search ended in October 2021. This is explained by the fact that the publication

Table 5.2: *Type and number of selected peer-reviewed literature.*

Type and number of experiments	**Number**
Original research paper	30
Synthesis and review	8
Meta-analysis	1

of the selected peer-reviewed literature focused on the impact of changing climatic drivers on soil processes and functioning was mainly published after 2015. The interest of scientific community to better understand the response of terrestrial ecosystems and soils to climate change has increased over the past decade.

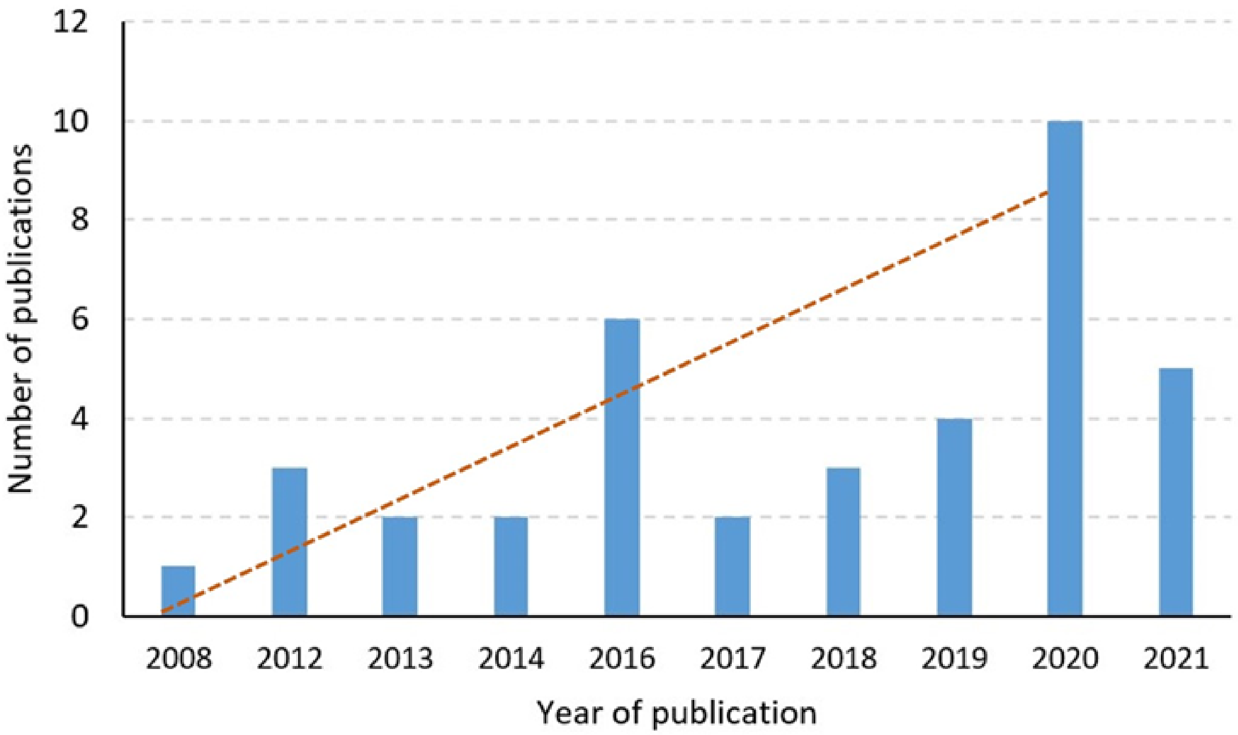


Figure 5.3: Overview of the selected digital peer-reviewed literature published until October 2021 and grouped per publication year. There is an increasing trend in the number of publications.

Although this synthesis mainly focused on studies carried out in grassland and cropland, we have also selected peer-reviewed literature that considered other ecosystem types to have a more comprehensive framework of the implication of climate drivers on soil properties and functioning. Therefore, 4 types of land use were included in this report (Table 5.3). Cropland and grassland were investigated in most of the experimental studies (56%), followed by mixed heterogeneous areas (36%), and meadow/prairie (8%).

A further classification of the selected peer-reviewed literature was done considering the geographic coverage of the experimental studied. Here, a national publication refers to a study carried out in one or more locations of a specific country, a regional publication describes research investigating effects for part of Europe (at least two Countries), and global publication refers to meta-analyses or synthesis and reviews carried out in some countries worldwide. Particularly, the selected peer-reviewed literature focused on studies and observations referring to different scales from national to global, with a greater concentration of data collected in field experiments carried out in Europe

Table 5.3: Type of land use, reporting the number of records as found in peer-reviewed selected literature.

Type of land use	Number
Cropland	12
Grassland	16
Meadow/Prairie	4
Mixed heterogeneous areas[1]	18

[1] Mixed heterogeneous areas include heathland (5), forest (8), peatland (2), steppe (2), and tundra (2)

(47.4%), worldwide (26.3%), or at local level in one Country outside Europe (26.3%), especially in the United States (USA; 50% of the local studies outside Europe), as shown in Table 5.4.

Table 5.4: Spatial level of research and number of records of selected peer-reviewed literature.

Spatial level	Number
National	27 (17 within Europe + 10 outside Europe)
Regional (European level)	1
Global	10

5.4.1 Approaches to assess adaptation and response of soil properties to climate drivers

Extreme climatic events are predicted to increase in frequency and magnitude in the near-future, with strong implications for soils and ecosystems (Kreyling et al., 2017; Rustad, 2008). As stated in the most recent literature on this topic, the ecosystem climate change experiments represent a crucial instrument to study the adaptive response of ecosystems to climate change (Roy et al., 2021; Vanderkelen et al., 2020). Generally, in this type of experiments, different climatic variables are altered (e.g., temperature, precipitation, and CO_2 concentration) as single- or multi-factor. Generally, in these experiments one or more climate drivers are altered, while all other variables do no change and are held equal between the different group of treatments.

In this synthesis, field experimental studies (i.e., manipulation, lysimeter, and ecotron experiments) or SFT substitution approach that investigate the single- or the multi-factorial effects of climate drivers (e.g., warming and extended drought) and elevated atmospheric CO_2 on soil properties and functioning were considered. Particularly, we focused on determining how properties of agricultural and grassland soils can be altered by single or simultaneous climate driver changes and how such soils can adapt to these climatic changes.

Table 5.5 summarizes the type and number of experiments that were included in the selected peer-reviewed literature. The most widespread type of experiment used to assess the single- or multi-factor effects of climate drivers on soil properties is represented by manipulation field experiment (30 input rows, 73.2%), followed by SFT substitution approach (5 input rows, 12.2%). Conversely, the lysimeter, ecotron, and integrated novel approach experiments were less adopted in the peer-reviewed literature we have selected to compile this synthesis (2 input rows each, covering together 14.6% of the total evaluated experiments).

Table 5.5: Type and number of experiments analyzed in this synthesis.

Type of experiments	**Number**
Manipulation	30
Space-for-time substitution	5
Lysimeter	2
Ecotron	2
Integrated novel approach	2

Manipulation experiment

Most authors agree that field manipulation experiments are powerful tools to understand ecological processes (Smith et al., 2014; Kreyling et al., 2017) and resilience of soils in the face of climate change (e.g., Breitkreuz et al. (2021), Alatalo et al. (2017), Carey et al. (2016)). As stated by Rustad (2008), experimental manipulations allow to better understand the the cause-and-effect relationships and the responses of ecosystems to single or multiple elements of global in both short- and long-term. Soil response to climatic extremes such as drought events is currently studied worldwide in a growing number of field experiments that predominantly use rain-out shelters (e.g., Kundel et al. (2018)).

Experimental manipulations can help us to understand the adaptative response of ecosystem or soil variables to single- or multiple-factor climate drivers (Rustad, 2008). However, results from short-term manipulation experiments may be transient, thus it is important setup long-term ecosystem manipulation experiments validate this concern and incorporate the findings into soil-crop and ecosystem models.

Space-for-time substitution approach

SFT substitution approach is commonly used in ecology and terrestrial systems to estimate implications for ecosystem functions. It refers to the extrapolation of a temporal trend from a series of different-aged samples (Pickett, 1989). The SFT is a type of "natural experiment" (Walker et al., 2010) that mimics a forecasted change over time, where spatially separated zones along a natural climatic gradient (Fleischer and Sternberg, 2006) serve as proxies for predicting temperature and/or precipitation changes (Rustad, 2008). The SFT approach is an indirect method used for investigating and understanding the effects of climatic variation on ecosystems Koch et al. (1995). To better quantify these effects on soil properties and functioning, specific environmental factors such as altitude and topography must be also considered in the same gradient framework (Dunne et al., 2003, 2004). Particularly, climatic time-series collected in a multiple-site gradient area allow to simulate climate change scenarios in such area ranging from no climate change (current climate) to altered temperature (warming) and/or precipitation (droughts and floods).

Lysimeter experiment

Weighable lysimeters are vessels filled with disturbed or undisturbed soil volumes, isolated from the surrounding field conditions. They are frequently used tools to measure water and matter fluxes in the unsaturated and saturated zone of the entire soil profile (up to several meters deep) and can provide accurate and precise observations up to field scale. Frequently, they are used to quantify the impacts of climate variables on the soil–plant system such as the influence of higher soil temperature and CO_2 concentration on water budget C and N cycling. A more detailed description of lysimeters is reported in (Groh et al., 2016, 2020).

Ecotron experiment

Ecotron is an experimental facility including a set of meso- macro-cosmos (i.e., replicated enclosures) that is designed to host ecosystems samples and allow realistic simulations of aboveground and belowground environmental conditions by automatically measuring ecosystem processes. Thus, it provides continuous information on ecosystem functioning (e.g., fluxes of energy and matter). Ecotrons used enclosures composed by two parts: a lysimeter for the soil and an aerial compartment around the canopy. A more detailed description of ecotrons is reported in Granjou and Walker (2016), Roy et al. (2021), Schmidt et al. (2021).

5.4.2 Effects of climate drivers and enhanced CO_2 concentration on soil properties

Table 5.6 lists the main soil variables that were investigated in study described in the selected peer-reviewed literature as well as the number of studies grouped per type of individual or combined climate variables (i.e., altered temperature, precipitation, and enhanced CO_2 concentration). This synthesis covers more than 30 soil variables, encompassing a wide range of soil characteristics such as soil GHG emission, soil water content and hydraulic properties, C and N cycling, mesofauna (e.g., earthworms and nematodes), microbial community (e.g., fungal and bacteria), and enzyme activity. Regarding climate variables, no publications investigated the single effect of enhanced CO_2 on soil properties and functioning, while 7 and 15 publications specifically investigated the individual effect of altered temperature and precipitation, respectively. On the other hand, the combined effect of climate variables (i.e., "CO_2 + T", "CO_2 + P + T", or "P + T") were investigated in 16 publications (Table 5.6).

Table 5.6: *List of main soil variables investigated in the selected studies to assess the effects of individual and combined climate drivers (i.e., decreased and/or increased temperature and precipitation) and CO_2 concentration on soil.*

Soil variable	T	P	CO_2	CE	Reference
Rs, SOC, GHG, MBC, MBN, microbial community, enzyme activity, Total and mineral N, belowground biomass		x			Abbasi et al. (2020)
Microbial community		x			Bardgett and Caruso (2020)
Physical (e.g., structure, texture, compactness, pore size and pore distribution) and biological (e.g., microbial and faunal biomass and community, rooting depth and root distribution)		x			Beier et al. (2012)
Hydraulic properties		x			Caplan et al. (2019)
Moisture, hydrophobicity (water repellence)		x			Gimbel et al. (2016)

Table 5.6 – *Continued from previous page*

Soil variable	T	P	CO_2	CE	Reference
Water storage, crop water use efficiency		x			Groh et al. (2020)
Moisture, temperature		x			Grysko et al. (2021)
Near-saturated hydraulic conductivity, infiltration		x			Hyväluoma et al. (2020b)
Water content, microbial community, C, N		x			Khalili et al. (2016)
Water content, evapotranspiration		x			Paschalis et al. (2020)
Water content, evapotranspiration		x			Rahmati et al. (2020)
Moisture		x			Robinson et al. (2019)
C, N		x			Schädler et al. (2019)
Water, Rs		x			Vicca et al. (2014)
C, N, moisture, and mites	x				Alatalo et al. (2017)
Microbial community composition	x				Breitkreuz et al. (2021)
Rs	x				Carey et al. (2016)
Rs, GHG, moisture, temperature	x				Roy et al. (2021)
Gross N mineralization, nitrification, abundance of ammonia-oxidizing archaea and bacteria, and other supporting soil parameters including gravimetric water content, concentrations of soil ammonium and nitrate, dissolved organic nitrogen and dissolved organic carbon	x				Wang et al. (2016)
Water holding capacity, SOM	x				Werner et al. (2020)
Belowground biomass, C, water content, MBC, MBN, bacterial and fungal biomass	x				Yu et al. (2018)
Belowground biomass, Rs, C storage, and nutrient cycling				x	Dieleman et al. (2012)
Soil C				x	Dietzen et al. (2019)
Water balance components				x	Forstner et al. (2021)
Dissolved inorganic N, mineral N, N_2O emission, C, N, evapotranspiration				x	Giraud et al. (2021)
Water content				x	Groh et al. (2016)
Moisture, CH_4 and CO_2 emission					Hanson and Walker (2020)
Moisture				x	Kundel et al. (2020)
MBC, MBN, microbial community composition				x	Li et al. (2017a)
Aggregate dynamics, SOM, CO_2 flux				x	Najera et al. (2020)
Microbial biomass, nematode densities				x	Okada et al. (2014)
MBC, CO_2 flux, temperature, moisture				x	Poll et al. (2013b)
GHG emission				x	Pütz et al. (2016)
Rs, N mineralization				x	Rustad (2008)
Earthworm community, moisture, pH				x	Singh et al. (2021)
Moisture, Rs,				x	Suseela et al. (2012)
Water content, water tension, electrical conductivity, temperature				x	Vanderkelen et al. (2020)
C, N, MBC				x	Zhou et al. (2013)
Total	7	15	0	16	

Note for experimental factors: T (altered temperature), P (altered precipitation), enhanced CO_2 concentration (CO_2) and Combined Effects (CE).

From each selected peer-reviewed literature, the most relevant information such as type of experiment (i.e., manipulation, SFT, econtron, and integrated methods), experimental factors (i.e., climate variables, individual: "P" and "T"; combined: "CO_2 + T", "CO_2 + P + T", or "P + T"), spatial level of research (national, European, global) and main conclusions was extracted and summarised in Table 5.7. Since two studies Forstner et al. (2021) and Rahmati et al. (2020) investigated two different approaches, a total of 40 records were listed in Table 5.7.

Table 5.7: List of type of field experiments, investigated factor(s), and main conclusions from the selected studies, examining the effects of individual and combined climate drivers (i.e., decreased and/or increased temperature and precipitation) and enhanced CO_2 concentration on soil functioning.

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
1	Manipulation	P	Abbasi et al. (2020)[3]	global	grassland	• Comparative analysis of 16 meta-analyses on the effects of precipitation changes on soil response variables. • Strong agreement that belowground C and N cycling accelerate under increased precipitation, while bacterial and fungal communities are relatively resistant to decreased precipitation. • More attention paid to fluxes and pools of soil C, N, P, and microbial biomass than to the rates of the processes involved.
2	Manipulation	P	Bardgett and Caruso (2020)[2]	global	grassland	• Need for new approaches to quantify resistance and resilience of soil microbial communities and to identify thresholds for transitions to alternative states. • High-resolution time series coupled with gradient designs will enable detecting response patterns to interacting drivers like drought. • Future studies should use environmental gradients to track soil microbial community responses to climate extremes in space and time.
3	Manipulation	P	Beier et al. (2012)[2]	global	grassland, cropland	• Past and ongoing precipitation experiments provided important information on how water regulates ecosystem processes. However, they do not adequately represent global biomes nor forecasted precipitation scenarios. • Need for new precipitation experiments in biomes and ambient climatic conditions poorly studied applying relevant complex scenarios including changes in precipitation frequency and magnitude, seasonality, extremity and interactions with other global change drivers.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
4	Manipulation	P	Caplan et al. (2019)[1]	local	prairie	• A 35% increase in water inputs substantially reduced infiltration rates and modestly increased water retention in soils from a 25-year precipitation manipulation experiment. • These shifts could have been catalyzed by greater pore blockage by plant roots and reduced shrink-swell cycles. Given the expected changes in precipitation regimes, shifts in soil structure could occur over broad regions more rapidly than expected and thus alter water storage and movement in numerous terrestrial ecosystems. • The response of soil respiration to temperature largely unaltered with experimental warming.
5	Manipulation	P	Gimbel et al. (2016)[1]	local	forest	• Dye tracer experiments in six forest sites forced into drought conditions showed changes in infiltration - from regular and homogeneous flow to fast preferential flow – and water repellence. • The “drought history” of a soil is more important than the actual antecedent soil moisture status regarding hydrophobicity and infiltration behaviour. • Drought effects on infiltration need to be considered in hydrological models to obtain realistic predictions concerning water quality and quantity in runoff and groundwater recharge.
6	Manipulation	P	Grysko et al. (2021)[1]	local	tundra	• Improvement and 2-years validation of an automated rainfall manipulation system adapted to the cold, harsh conditions of the Siberian Arctic tundra.
7	Manipulation	P	Hyväluoma et al. (2020b)[1]	local	peatland	• The study investigated the interactive effects of precipitation manipulation and nitrogen addition on soil properties in California grassland and shrubland. • Near-saturated hydraulic conductivity decreases rapidly after reclamation of peat soil. • This transient phase may continue for decades before reaching a new steady state of significantly lower hydraulic conductivity.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
8	Manipulation	P	Khalili et al. (2016)[1]	local	grassland	• The response of soil microbial biomass to precipitation and/or N manipulation was tested in grassland and shrubland of a semi-arid area. • The interaction between drought and N addition had negative effects on microbial biomass and increased labile C and N pools, therefore building-up available N and inhibiting soil C cycling. • Microbial composition differed more strongly by vegetation type than with environmental change treatments.
9	Integrated novel approach	P	(Kundel et al., 2018, 2020)[1]	local	cropland	• Authors present and test the performance of a rain-out shelter for climate change experiments in agroecosystems. • Microclimatic conditions and production of above-ground biomass were unaffected by the rain-out shelter treatments. Soil moisture differences between the different treatments remained constant throughout the experiment. • Short-term effects of experimental warming and precipitation manipulation on soil microbial biomass C and N, community substrate utilization patterns, and community composition.
10	Manipulation	P	Paschalis et al. (2020)[1]	global	grassland	• Intercomparison of 10 terrestrial biosphere models to reproduce the observed sensitivity of ecosystem productivity to rainfall changes. • Inter-model variation is generally large and model agreement varies with timescales. • Models on average overestimate the relationship between ecosystem productivity and mean rainfall amounts across sites. • Most models had a low capacity in reproducing the observed magnitude of productivity changes. • Models better reproduced the observed productivity responses due to rainfall exclusion than addition.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
11	Manipulation	P	Rahmati et al. (2020)[1]	local	grassland	• A The presence of a decreasing trend in the phase shift between soil water content and ETa, and an increasing phase shift between SWC and WSI. • Weighable lysimeters were used to study the relation between soil water content and the actual evapotranspiration (ETa) of grassland under two different climate regimes. • Increasing dryness at the energy-limited site led to more temporal variability of soil water content at the annual timescale. • Wavelet coherence analysis showed a reduction of the phase shift between soil water content and ETa at an annual scale caused by the increase in dryness during the measurement period.
12	Manipulation	P	Robinson et al. (2019)[1]	local	heatland	• A long-term manipulation experiment supports the existence of drought induced alternative stable soil moisture states (irreversible soil 12wetting) in upland Atlantic heath. • Manipulated repeated moderate summer drought, and intense natural summer drought both lowered resilience resulting in shifts in soil moisture dynamics. • Intense summer drought, superimposed on the experiment, caused an unexpected erosion of resilience and a shift to an alternative stable soil moisture state both for the experimental drought manipulation and control plots, impairing the soil from rewetting in winter.
13	Manipulation	P	Vicca et al. (2014)[2]	global	grassland	• The data of 38 experiments were gathered to test the hypothesis that a model parameterized with data from the control plots (using soil temperature and water content as predictor variables) could adequately predict soil CO_2 efflux under altered rainfall patterns. • Regression tree analysis demonstrated that such hypothesis could be rejected only for experiments with measurement intervals of less than 11 days. • Climate change amplifies gross nitrogen turnover in montane grasslands of Central Europe in both summer and winter seasons. • Future experiments should conduct high-frequency soil CO_2 efflux measurements and should consider both instantaneous responses and the potential legacy effects of climate extremes.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
14	Manipulation	T	Alatalo et al. (2017)[1]	local	meadow	• The impact of 20 years of experimental warming on soil properties and soil mites in three contrasting plant communities in alpine/subarctic Sweden is reported. • Long-term warming decreased juvenile oribatid mite density, indicating that juvenile mites may be more vulnerable to global warming than adult stages. • Results suggest that global warming may cause C and N losses in alpine and tundra mineral soils and that its effects may differ at local scale.
15	Manipulation	T	Breitkreuz et al. (2021)[1]	local	cropland	• Bacterial community composition strongly driven by soil type and drought. Enzyme activities and functional gene abundances related to C degradation increase under drought in the rhizosphere of a wheat cultivar in organic farming. Decadal-scale shifts in soil hydraulic properties as induced by altered precipitation.
16	Manipulation	T	Carey et al. (2016)[2]	global	cropland, forest, grassland, heathland, meadow, peatland, tundra	• The data on soil respiration, moisture and temperature of 27 temperature manipulation studies, spanning nine biomes and over 2 decades of warming, are synthesized. • No significant differences were observed in the temperature sensitivity of soil respiration between control and warmed plots in all biomes, except for deserts and boreal forests. • Across all non-desert biomes, respiration rates with and without experimental warming follow a Gaussian response, increasing with soil temperature up to a threshold of25 řC, above which respiration rates decrease with further increases in temperature.
17	Manipulation	T	Werner et al. (2020)[1]	local	forest	• Short- and long-term warming alters soil microbial community and relates to soil traits. • Formerly heated plot remained warmer and drier than the control plot during the suspension period, despite having received no artificial warming for several months. Reduced soil water storage capacity could make both ecosystems and human infrastructure more sensitive to the weather variability. This could result in reduced forest growth and carbon storage, further reinforcing climate change.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
18	Manipulation	T	Yu et al. (2018)[1]	local	steppe	• A 4-years field experiment established to compare the seasonal effect of long-term warming and short-term acute warming on soil microbial communities in a desert grassland ecosystem. • The short-term acute warming regime significantly increased the bacteria/fungi and the Gram+/Gram- ratios in August. • Alterations in the structure of soil microbial communities may strongly depend on growing seasons and soil nutrient status might have a profound impact on soil microbial communities' responses to climatic warming. • Warming rather than increased precipitation increases soil recalcitrant organic carbon in a semiarid grassland after 6 years of treatments
19	Manipulation	CO_2 + T	Dieleman et al. (2012) [2]	global	grassland, forest	• Elevated CO_2 concentration combined with warming stimulates fine root biomass production and soil respiration. • Less-than-additive responses of aboveground biomass to the combined treatment. • Need for more long-term multifactor manipulation experiments in the future.
20	Manipulation	CO_2 + T	Forstner et al. (2021)[1]	EU	grassland	· Manipulation: higher CO_2 concentration on ETa largely compensated by higher temperatures.
21	Manipulation	CO_2 + T	Okada et al. (2014)[1]	local	cropland	• A 2-year Investigation on the effects of a predicted elevation in CO_2 and temperature over the next 50 years on the dynamics of dominant nematode taxa and their food source in a flooded paddy field equipped with a FACE + heater system. • An elevation in temperature increased rice root biomass, decreased microbial biomass and retarded reproduction in the nematode taxa. • Elevated CO_2 increased rice root biomass but did not affect microbial biomass or reproduction of any type of nematode taxon.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
22	Manipulation	CO_2 + P + T	Dietzen et al. (2019)[1]	local	grassland, heatland	• Exposition of a temperate heath/grassland to elevated CO_2, warming, and drought for 8 years increased soil C stocks of 0.120 ś 0.043 kg C m^2 year^1 with no sign of slowed accumulation over time. • Response to elevated CO_2 not affected by simultaneous exposure to warming and drought. • Potential for enhanced soil C sequestration in some ecosystems to mitigate increasing atmospheric CO_2 concentrations under future climate conditions.
23	Manipulation	CO_2 + P + T	Hanson and Walker (2020)[2]	global	grassland, forest	Retrospective summary of several key publications on experimental manipulations field experiments and suggestions to: • Relate mechanistic understanding and methodological needs in future experiments for elevated CO_2 atmospheres and anticipated warming scenarios. • Integrate ecosystem-scale manipulations with focused process-based manipulations, networks, and large-scale observations for a more complete understanding of eco-system responses, context dependence, and the extrapolation of results.
24	Manipulation	CO_2 + P + T	Poll et al. (2013b)[1]	local	cropland	• A two-years experiment (TERENO-SOILCan) was established in Germany to investigate effects of elevated temperature and altered precipitation on soil respiration in an arable soil. • Temperature elevation significantly reduced Q_{10} values of soil respiration by 0.7–0.8 whereas altered precipitation showed only minor effects. • The moisture regime of soils under elevation of temperature will largely determine whether different soils will serve either as C sources or as C sinks. • Despite the important feedback mechanism of ecosystems to climate change, there is still a lack of experimental observation in agricultural ecosystems.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
25	Manipulation	P + T	Li et al. (2017a)[1]	local	forest	• Warmed air temperature and decreased or increased precipitation manipulation tested as climate change drivers for soil microbial biomass indicators. • Decreased and increased precipitation significantly reduced microbial biomass C and N in unwarmed plots. • Warming enhanced community substrate utilization among all precipitation manipulation plots. • Warming and/or precipitation manipulation treatments significantly altered Zygomycota abundance.
26	Manipulation	P + T	Najera et al. (2020)[1]	local	forest	• Increasing the temperature and the number of drying/rewetting cycles at 25 řC decreased substrate use efficiency of particulate lignocellulose. • Drying/rewetting cycles at warm temperatures accelerated OM turnover due to preferential use from fPOM, increasing macroaggregates at the expense of microaggregates.
27	Manipulation	P + T	Singh et al. (2021)[1]	local	grassland	• Climate had species-specific effects on active earthworms, but few interactions with land-use type. • Intensive grassland management decreased, but sheep grazing favoured, active earthworm populations. • Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. • Strong seasonal variations in earthworm activity periods will be modulated by climate change.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
28	Manipulation	P + T	Suseela et al. (2012)[1]	local	forest	• The effect of warming and altered precipitation on the rate and temperature sensitivity of heterotrophic respiration (Rh) was measured inside deep collars that excluded plant roots and litter inputs. • Drought reduced Rh both annually and during the growing season, whereas warming increased Rh only in early spring. • The effect of climate treatments on the temperature sensitivity of Rh depended on the season. Apparent Q_{10} decreased with high warming (about 3.5řC) in spring and fall. Presumably due to limiting soil moisture, warming and precipitation treatments did not affect apparent Q_{10} in summer.
29	Manipulation	P + T	Zhou et al. (2013)[1]	local	steppe	• Long-term field experiment to test the effect of increased temperature and/or precipitation on SOC fractions in a semiarid grassland. • Neither warming nor increased precipitation affected total SOC and stable SOC when manipulated separately. • Significant interactive effects of warming and increased precipitation on labile SOC and recalcitrant SOC at the 0–10 cm depth. • Absolute increase of SOC in the recalcitrant SOC pool much greater than the decrease in labile SOC suggests that soil C storage at 10–20 cm depth may increase with increasing temperature in this semiarid grassland.
30	SFT	P	Groh et al. (2020)[1]	local	cropland	• Rainfall experiment (TRainEx) to simulate future summer precipitation scenarios. • Soil water storage dynamics vulnerable to droughts because of insufficient refilling of water storage capacity. • No effect of drought on grain yields due to higher water use efficiency.
31	SFT	P	Rahmati et al. (2020)[1]	local	grassland	• Please see comments in row 11

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
32	SFT	T	Wang et al. (2016)[1]	local	grassland, cropland, forest	• Consequences of climatic change for soil N turnover in montane grasslands investigated in plant-soil mesocosms along an elevational gradient resulting in an increase of the mean annual temperature by about 2 řC while decreasing precipitation from about 1500 to 1000 mm. • Dynamics of gross N turnover and ammonia-oxidizing bacteria and archaea in soils was monitored over an entire year after three years of equilibration. • Gross N turnover and gene levels of ammonia-oxidizing bacteria and archaea showed pronounced seasonal dynamics but were restricted to the 2-6 cm topsoil. • Highest gross N turnover and abundance of ammonia oxidizers were observed in frozen soil of the climate change site, likely due to physical liberation of organic substrates and their rapid turnover in the unfrozen soil water film.
33	SFT	CO_2 + T	Forstner et al. (2021)[1]	EU	grassland	• SFT: plant water availability as the most critical factor.
34	SFT	P + T	Giraud et al. (2021)[1]	local	cropland	• In the short term, fertilizer should be applied early in the growing period to increase N uptake and decrease N losses. • In grasslands, a shift from energy-limited to water-limited conditions will have a limited effect on gaseous N emissions and nitrate concentrations in the groundwater because higher N concentrations are compensated by lower leaching rates.
35	Lysimeter	P + T	Groh et al. (2016)[1]	local	cropland	• Importance of a proper control of the lysimeters bottom boundary conditions in space-for-time studies that investigate the influence of climate change by transferring lysimeter along climate gradients. • Different climate conditions between sampling and installation site did not show a strong influence on the bottom boundary control of lysimeters when the groundwater table depth was assumed to remain constant.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
36[ğ]	Lysimeter	P + T	Pütz et al. (2016)[1]	local	grassland	• Description of the general design of the German SOILCan lysimeter-network experiment, formed by a network of 132 fully automated lysimeter systems installed at 14 highly equipped experimental field sites across four observatories. • Lysimeters are either being operated at or near their original sampling location or were transferred within or between the observatories thereby using temperature and rainfall gradients to mimic future climatic conditions. • Relevant state variables of grassland and arable ecosystems are monitored characterizing climate, hydrology and matter fluxes into the atmosphere and within the hydrosphere as well as plant species diversity.
37	Ecotron	T	Roy et al. (2021)[2]	local	prairie	• The paper describes 13 advanced controlled environment facilities for experimental ecosystem studies (ecotrons) and discusses how the methodology for ecology, agronomy and environmental science can be improved with them.
38	Ecotron	P + T	Vanderkelen et al. (2020)[1]	local	heatland	• A novel method for assessing climate change impacts with Ecotron experiments is tested in one of the European Ecotron facilities. Using data from the best-performing regional climate model simulation for the ecotron site, it generates climate forcing along a gradient representative of increasingly high global mean air temperature anomalies. • With the approach proposed, Ecotron facilities become able to assess ecosystem responses on changing climatic conditions, while accounting for the co-variation between climatic variables and their projection in variability.
39	Integrated novel approach	P	Schädler et al. (2019)[1]	local	cropland	• The Global Change Experimental Facility (GCEF), combining mobile roofs and irrigation systems in 400 m^2 field plots, allows the reduction (in summer by c. 20%) and increase of rainfall (in spring and autumn by c. 10%) according to future scenarios superimposed on the ambient variation in precipitation. • Five different land use types (two farming systems, three grasslands), differing in land use intensity, are submitted to ambient and future climatic conditions. • The large plot size and the technical configuration allow the establishment of realistic land use scenarios and long-term observations of responses of ecosystem functions and community dynamics on relevant temporal and spatial scales.

Table 5.7 – *Continued from previous page*

N.	Exp. type	Exp. factor(s)	Author(s)	Level	Land use	Main conclusions
40	Integrated approach novel	CO_2 + P + T	Rustad (2008)[2]	global	cropland, grassland	• Recommendations reflecting discussions within the Terrestrial Ecosystem Response to Atmospheric and Climatic Change (TERACC) international network of global change scientists. • Better integration between experiments and models, and amongst experimental, monitoring, and space-for-time studies. • Explicit inclusion of biodiversity, disturbance, and extreme events in experiments and models. • Consideration of timing vs intensity of global change factors in experiments and models. • Evaluation of potential thresholds or ecosystem 'tipping points'. • Increased support for model-model and model-experiment comparisons.

Type of peer-reviewed literature: [1]Original research paper, [2]Synthesis and review, [3]Meta-analysis. Experimental factors: enhanced CO_2 concentration (CO_2), P (altered precipitation), T (altered temperature). [ğ]Lysimeter network for observing soil processes and plant diversity as affected by climate change

In precipitation manipulated field experiments the effect of a treatment is generally assessed compared to a control or a reference condition (Beier et al., 2012). Many authors agree that altered precipitation conditions affects both soil abiotic (e.g., water availability, infiltration, and runoff) and biotic (e.g., microbial community and enzyme activity) processes (Alster et al., 2013; Caplan et al., 2019; Wang et al., 2021). For instance, an increase in precipitation regime may accelerate SOM decomposition and plant growth due to higher water availability in soil compared to unchanged precipitation condition, while drought events may reduce the decomposition due to the increased physical protection of SOM (Vasconcelos et al., 2004; Wang et al., 2021; Wu et al., 2011). These behaviours may have direct consequences for soil C pools (Fröberg et al., 2008). Abbasi et al. (2020) conducted a comparative analysis of 16 peer-reviewed meta-analyses, exclusively oriented on field studies (covering different land use, mainly based on grassland) where the magnitude of precipitation was manipulated. Particularly, the authors deeply evaluate the effects of altered precipitation on different soil response variables (n=42), covering a wide range of soil processes (e.g., GHG fluxes, C and N cycling, microbial community, and enzyme activities). Much attention has been paid to fluxes and pools. The authors found strong agreement among the examined studies that belowground C and N cycling are highly influenced by changes in precipitation regimes. Both cycles speed up under increased precipitation and slow down under decreased precipitation. Conversely, bacterial and fungal communities are relatively resistant to decreased precipitation.

It is well-known that precipitation regimes are expected to change at accelerating rates globally. Thus, changes in soil structure could occur over broad regions, thus altering water infiltration and storage in many terrestrial ecosystems. In this context, the recent paper published by Caplan et al. (2019) specifically focused on the decadal-scale shifts in soil hydraulic properties as induced by altered precipitation. In a typical prairie of Kansas (US) managed over 25-year under a precipitation manipulation experiment, the authors found that soil with a 35% increase in water inputs substantially reduced infiltration rates and modestly increased water retention. The authors suggested that the shifts reduced shrink-swell cycles and it can be catalysed by greater pore blockage by plant roots.

In a manipulation field experiment setup in a temperate agricultural ecosystem in Germany, Poll et al. (2013b) tested the combined effects of altered temperature (warming) and precipitation (amount and frequency) on soil properties. Interestingly, the authors found a negative effect of elevated soil temperature on soil moisture, which could be explained by increasing evapotranspiration (Eta). This might induce water limitation during the dry summer, which negatively affects microbial abundance and activity. Compared to altered temperature, precipitation showed minor effects because it was manipulated only three months per year. Thus, the adaptative response of soil microorganisms to increased drought stress during summer may require more time.

Soil temperature is affected indirectly or directly by several factors such as solar radiation, air temperature, topography, soil water content, soil texture, and plant cover Climate change adaptation through soil and crop management: synthesis and ways forward (Paul et al., 2004). As stated in previous studies (Ćirić et al., 2017; Dalias et al., 2001; Sanderman et al., 2003), the increase of soil temperature directly influences ecosystem functioning and soil microbial processes linked to soil respiration and SOM decomposition, by altering soil processes. However, the response of soil properties and functioning to altered temperature (warming) is still uncertain and generally unknown.

Investigating the interactions between main climate drivers (e.g., changes in temperature and precipitation) and increase of atmospheric CO_2 concentration is crucial to understand the potential feedbacks between future CO_2 concentration and soil properties. Generally, changes of temperature (warming) and precipitation (summer drought) combined with increase of atmospheric CO_2 concentration are considered one of the most important pressure factors that affects soil biodiversity

(Gardi et al., 2008), SOC concentration, and turnover rate (Hillel and Rosenzweig, 2011). However, their effects are rarely additive as stated by Dieleman et al. (2012) and Larsen et al. (2011). Moreover, variation of temperature and precipitation combined with soil types makes the response of soils to climate drivers difficult to predict (Ćirić et al., 2017). Dietzen et al. (2019) investigated the effects of the increase of atmospheric CO_2 concentration combined with the changes of temperature (warming) and precipitation (extended drought) on soil water variation and SOC stocks to 30 cm depth over an experimental period of 8 years. They focused particularly on determining the effect of enhanced CO_2 on soil C stocks and how its effect may be altered by simultaneous changes in temperature (warming) or soil water (drought).

5.5 Conclusion

This synthesis resumes the state of the art of knowledge and knowledge gaps on impacts of changing climatic drivers on soil properties and functioning and adaptation of soil variables to climate change. The report provides a perspective on how individual and combined effects of climate drivers (decreased and/or increased temperature and precipitation) and enhanced CO_2 concentration affect soil functioning and belowground processes as well as the responses of soil to such changes. This report was written by CREA (Italy) in collaboration with EV-ILVO (Flanders, Belgium) and SLU (Sweden), via specific search criteria (e.g., type of literature, land use, climate driver, and type of experiment) and a dedicated peer-reviewed literature analysis. A total of 39 peer-reviewed literature among original papers, synthesis and report, and meta-analysis were selected, and 41 literature items were analysed (Table 5.7), since two studies described the effects of climate drivers on soil processes and functioning in more than one experimental category.

Human-induced climate change is expected to continue altering climate drivers (e.g., air temperature and precipitation) and enhancing CO_2 concentration in the atmosphere, also in the near-future. Changes in these conditions will alter soil processes and affect soil physical (e.g., water availability), chemical (e.g., SOM) and biological (e.g., microbial community and enzyme activity) functioning, which are of critical importance for the agricultural sector in terms of plant development and food production.

5.5.1 Limitation of this synthesis

Although this synthesis provides a clear overview of the current knowledge on the adaptative response of key soil properties and functioning to climate change based on field approaches (e.g., manipulation experiments and SFT) mainly adopted under semi-natural ecosystems, some limitation occur. Firstly, to maximize the geographic and cropland coverage of the studies, we only focused on digital peer-reviewed scientific articles written in English language, leaving out scientific articles published in paper format with no current online access and other publications such as books, book chapters, and grey literature. The restriction used for the search criteria may have limited the number of studies because no other type of documents written in English or other languages of the CLIMASOMA project consortium was included in the search criteria. Thus, relevant studied for some European environmental zones may not be considered. Secondly, the set of the selected peer-reviewed literature that fitted with our search criteria was unbalanced towards semi-natural ecosystems (e.g., grassland or mixed heterogeneous areas) in Continental, Atlantic, and Boreal environmental zones, compared to cropland in the same or in other pedoclimatic regions, such as the Mediterranean basin. Therefore, this synthesis did not provide a comprehensive set of experimental findings useful to predict the adaptative response of European agricultural soils to near-future climate change.

5.5.2 Recommendation and implication for future research

This synthesis has advanced our understanding on the impacts of climate drivers and enhanced CO_2 concentration on soil properties and functioning of few specific land use and systems. Interestingly, the variables receiving the greatest attention are generally the easier-to-measure. For instance, responses of soil variables such as SOC change, Rs, MBC, MBN, and enzyme activity have received more attention (e.g., Abbasi et al. (2020); Dieleman et al. (2012); Wang et al. (2016); Yu et al. (2018)), while responses of soil physical variables more related to aggregates, water infiltration, and storage have been less investigated (e.g., Beier et al. (2012); Caplan et al. (2019); Groh et al. (2020)). Therefore, predicting the individual and combined effects of climate change in different environmental zones, land use and soil management is of crucial importance to help us understand the complex mechanisms underlying the responses of soil system to climate change that are still not completely known. For instance, what are the most important mechanisms behind soil changes, and how quickly will total soil properties and functioning respond? To fill these knowledge gaps and provide scientific recommendations for national and international soil policy, the use of robust datasets from existing research on the response of soil to individual or combined climate drivers must be strengthen by new research on cropland, covering the most important European agro-environmental zones and soil type, also by promoting a better integration among observational, experimental, and modelling techniques that investigate single- and multi-factor effects. This aspect has been particularly stressed in a recent commentary published on Global Change Biology specifically addressed to advance the knowledge of the effects of climate change on different ecosystems (Hanson and Walker, 2020).

Chapter 6

Quantitative meta-analysis, publication bias and machine-learning to derive context-specific relationships

6.1 Summary

Saturated and near-saturated soil hydraulic conductivities K_h (mm.h^{-1}) determine the partitioning of precipitation into surface runoff and infiltration. They are fundamental to soils' susceptibility to preferential flow and indicate soil aeration properties. However, measurements of saturated and near-saturated soil hydraulic conductivities are time consuming. So-called pedotransfer functions are needed to estimate K_h from predictor variables. Since respective pedotransfer functions have been largely unsuccessful, recent studies have focused on assembling and analysing bigger databases, aiming at finding better predictors. In this work package, we collated OTIM-DB (Open Tension-disk Infiltrometer Meta-database), which builds on a meta-database published by *Jarvis, N., Koestel, J., Messing, I., Moeys, J., and Lindahl, A.: Influence of soil, land use and climatic factors on the hydraulic conductivity of soil, Hydrol. Earth Syst. Sci., 17, 5185–5195, 2013*. OTIM-DB increases the number of data-entries by a factor of approximately 1.5 compared to its predecessor and contains more detailed information on local climate as well as land use and management than its predecessor. In this study, we present OTIM-DB together with a meta-analysis on topsoil K_h from supply tensions ranging between 0 and 10 cm. We also included an attempt to build a respective pedotransfer function using a light gradient boosting model.

Our study confirmed significant correlations between climate variables as well as the elevation above sea level with K_h. While it seems very likely that these variables influence soil physical properties, the exact underlying mechanisms need to be investigated in future studies. We found indications that specific soil management practises lead to changes in K_h. They were increased under perennial cultures and decreased for no-till arable fields with annual crops and for compacted soil. Our data also confirmed that it is fundamental to take the time of the measurement after the last tillage operation into account to understand relationships between soil management and K_h. Note that the management impacts turned out to be dependent on the pedo-climatic context, as they only could be observed if variations in the latter were ruled out. Besides these results, we also found that the data availability for tension-disk infiltrometer data was too scarce and riddled with too many gaps for detailed analyses of other soil management impacts, more specific pedo-climatic context dependencies and publication bias. Furthermore, we found evidence that the available data was afflicted with experimenter bias. Altogether, it was not possible to predict K_h from the available data for new sites, which echoes results of similar attempts to build respective pedotransfer functions. More measurements with better documented meta-data and better suited predictor variables would

be needed for progress in this field. Studies quantifying soil structure evolution with respect to season, land use and soil management using X-ray imaging may turn out to provide useful information for more appropriate predictor variables for K_h.

6.2 Introduction

Soil climate models predict more frequent extreme events with the onset of global warming such as high intensity rainfall. To prevent water runoff and erosion on fields, the soils need to be able to conduct such large amounts of water in a short time. The soil property that matters is the saturated hydraulic conductivity K_s (mm.h^{-1}). It determines the partitioning of precipitation into surface runoff and infiltration. A large K_s reduces erosion risks and allows water to infiltrate into deeper soil layers, where it may replenish an important reservoir of plant available water or contribute to groundwater recharge. The hydraulic conductivity of a soil decreases with decreasing water content, i.e. with decreasing water saturation. The hydraulic conductivity in this so-called near-saturated range is likewise important. Soils with larger hydraulic conductivity near saturation K_h (mm.h^{-1}) tend to generate less water flow in macropore networks. Therefore, they are less susceptible to preferential flow (Larsbo et al., 2014) by which agrochemicals and other solutes quickly leach towards the groundwater. Moreover, large K_h also indicates a well-aerated soil, which drains faster and helps air to escape the soil in cases of heavy rainfall. This further reduces the risk of surface runoff and erosion as entrapped air strongly decreases soil hydraulic conductivity. Note that the index '*h*' indicates a matrix potential between 0 and 10 cm at which K_h was measured. References to K_h may also include K_s since for h == 0 cm, K_h == K_s.

Saturated hydraulic conductivity is measured either in the laboratory on small cylinders, usually with diameters <7 cm (Klute and Dirksen, 1986) or it is acquired from field measurements, either using single or double ring methods (Angulo-Jaramillo et al., 2000). In addition, the near-saturated hydraulic conductivities can be measured using a tension disk infiltrometer. The method is designed as a field method but has been occasionally applied in the lab. Using a tension disk hydraulic conductivities between ca. 0.5 and ca. 60 to 150 mm can be obtained, depending on the specifications of the infiltrometer. All measurement techniques for the saturated and near-saturated hydraulic conductivities are laborious, time-consuming and constrained to a relatively small soil volume.

It is therefore necessary to develop pedotransfer functions to estimate soil hydraulic conductivities for modelling applications (Bouma, 1989; Van Looy et al., 2017; Wösten et al., 2001). The development of a pedotransfer function requires a database from which it can be derived. For example, the well-known pedotransfer function ROSETTA (Schaap et al., 2001) is based on the open UNSODA database (Nemes et al., 2001). The equations published in Tóth et al. (2015) are derived from the proprietary EU-HYDI database (Weynants et al., 2013). The pedotransfer functions of Jarvis et al. (2013) are based on an unpublished meta-database containing tension-disk infiltrometer data.

Collecting published measurements of saturated and near-saturated hydraulic conductivity measurements into meta-databases and pairing them with other existing databases is essential to develop pedotransfer functions. A notable example is the SWIG database (Rahmati et al., 2018) that collates more than 5000 datasets from soil infiltration measurements, covering the entire globe. Another big effort in collecting information on saturated hydraulic conductivity is the newly published SoilKsatDB (Gupta et al., 2021a), which combines saturated hydraulic conductivity data from several large databases, amongst others UNSODA and SWIG, together with additional measurements published in independent scientific studies. However, none of the databases cited above provide open-access infiltration measurements at tension near-saturation (h >0 mm), which limits their use to estimations of saturated hydraulic conductivities.

Pedotransfer functions for saturated hydraulic conductivity exhibit rather poor predictive performance (Weynants et al., 2009; Jorda et al., 2015) . Early approaches, like HYPRES (Wösten et al., 1999) and ROSETTA, focused solely on soil properties like texture, bulk density and organic carbon content. Back then, it was not sufficiently recognized that soil K_S is mostly determined by the morphology of macropore networks, especially in finer-textured soils (Vereecken et al., 2010; Koestel et al., 2018; Schlüter et al., 2020). A pedotransfer function for K_S requires therefore ideally a database that contains direct information on the macropore network itself. But since such measures are more cumbersome and time-consuming to obtain (e.g. by X-ray tomography) than measuring hydraulic conductivity itself, it is more reasonable and makes more sense to use proxies from which the macrostructure in a soil can be inferred. Ideal candidates would be root growth and the activity of soil macrofauna, which both strongly determine the development of macropore networks in soil Meurer et al. (2020c). But also they are difficult to measure. More promising proxies are land use and farming practises, such as tillage or soil compaction due to trafficking. Plant growth and soil macrofauna are in turn influenced by the local climate. The climate also sets boundaries for the land use and the associated soil management practises, and thus provides feedback to root growth and macro-faunal activity. Wetting and drying cycles, and thus the formation and closure of cracks also are regulated by the climate. It is therefore not surprising that climate variables are typically correlated with saturated and near-saturated hydraulic conductivities (Jarvis et al., 2013; Jorda et al., 2015; Hirmas et al., 2018; Gupta et al., 2021b). Jorda et al. (2015) found that land use itself was the most important predictor for saturated hydraulic conductivity. The time of measurement of the hydraulic conductivity (or soil sampling) also has a crucial impact. In an agricultural soil, the hydraulic properties of a freshly prepared seedbed differ from those measured later at harvest. Several studies have demonstrated the evolution of hydraulic conductivity with time (Messing and Jarvis, 1990; Bodner et al., 2013; Sandin et al., 2017) . Soil management options (such as tillage or the use of cover crops) actively influence the soil saturated and near-saturated hydraulic conductivity. Information on their impact is therefore especially important, but so far has hardly been investigated in meta-analyses.

Quantitative analyses of meta-databases are referred to as meta-analyses. It often consists either of an exploratory data analysis or a comparison of effect sizes or both. The the second method compares effects of two different treatments, i.e. conventional and reduced tillage, on the target variables, in our case K_h. Individual source publications need to contain results for both treatments. The observed differences in each study are then averaged and interpreted. An example of such a study is Basche and DeLonge (2019). For the exploratory data analysis, data entries from the meta-database are evaluated using weighted correlations, regressions or cluster analyses. The weighting is important, because the source publications provide different amounts of data entries to the meta-database that are in turn summarised from varying numbers of replications. Data entries measured at the same field site need to be down-weighted, as they would otherwise introduce a bias that would make the respective site properties, e.g. the climate at this site, appear disproportionately important. Likewise, data entries that represent the average of several replications need to be up-weighted compared to data entries representing the average of only a single measurement.

Relationships between environmental data are often non-linear. In such cases, predictions made linear regressions contain considerable error due to under-fitting, i.e. introduced by using a linear model to express a non-linear relationship. Modern machine learning approaches have the advantage that they can model non-linear relationships. They also enable quantifications of predictor importance and their comparison, offering a way to compare categorical with numerical predictors. By singling out the most important predictors, context-specific relationships in dependence of these predictors can be evaluated, provided that the investigated dataset is large enough.

In this study, we investigated the effects of soil management practises on the saturated and near-saturated hydraulic conductivity, including analyses of publication bias. More specifically, we illustrated the statistical relationships between soil properties and pedo-climatic and agronomic factors and saturated and near-saturated hydraulic conductivity in the tension range from 0 to 10 cm. To our knowledge, a systematic and quantitative review on hydraulic conductivity over the entire near-saturated tension range has been missing in peer-reviewed literature. Through this work, we expanded and published the previously unpublished meta-database on tension-disk infiltration measurements that was first reported by Jarvis et al. (2013). We referred to this database as OTIM-DB in the following (Open Tension-disk Infiltrometer Meta-Database). It complements the currently available public databases that are strongly based on laboratory measurements or ring infiltrometer methods. OTIM-DB allows the investigation of systematic bias in saturated hydraulic conductivity measurements due to the method applied and supports the development of improved pedotransfer functions for saturated and near-saturated hydraulic conductivities.

In the first part of the report of CLIMASOMA WP4, we present OTIM-DB and undertake meta-analyses (TP1) and attempt to appraise publication bias in the included source-publications (TP2). In the second part, we discuss the result of a machine learning approach trained on the OTIM-DB data (TP3).

6.3 Meta-Database, OTIM-DB

6.3.1 Data collection

The first version of OTIM-DB was compiled for the study by Jarvis et al. (2013). The original database contained 753 tension-disk infiltrometer data entries collated from 124 source publications, covering 144 different locations around the globe. We have extended this database by 577 new tension-disk infiltrometer data entries from 48 additional studies that had been published after 2012. The search for publications was carried out between 2021-05-31 and 2021-06-23 using the queries and search engines detailed in Table S1.

We found 115 publications containing tension-disk infiltrometer measurements published in 2013 or later. We retained the data for further analysis when (i) K_h or the infiltration rate was measured at more than two tensions larger or equal 5 mm and (ii) sufficient meta-data on soil and site properties (at least soil texture) as well as soil management practises (at least land use and tillage) were available. When a publication solely reported infiltration rates, we calculated the hydraulic conductivity using the method of Ankeny et al. (1991). Only 45 of the 115 publications fulfilled the above-mentioned criteria. Table S2 summarises how many papers were rejected for which reasons. For 27 of the 45 retained studies, we digitised the published K_h values from figures using WebPlotDigitizer (open-source web-based software created by Ankit Rohatgi, `https://automeris.io/WebPlotDigitizer/`). For cases in which K_h measurements were mentioned in a publication, but the results were not reported, we contacted the corresponding authors. For three of these publications, we received the data in this fashion (Alletto et al., 2015; Larsbo et al., 2016; Meshgi and Chui, 2014).

In addition to adding data from new publications to OTIM-DB, we also revisited the studies already contained in the original database version and collected additional information on soil management practises associated with the measured data. For each soil management option, OTIM-DB contains two columns. In the first column, the information as given in the source publication is stored. The second column summarises this information into a few classes, which could subsequently be used in the meta-analysis. In this study, we investigated effects of land use, tillage system, soil compaction and day of measurement relative to the latest tillage operation on the field. A compaction class was assigned to a data entry only if the plot had been described as 'compacted' or 'not compacted' in the source publication. 'Compacted' data entries corresponded, for example, to infiltration measurements in wheel tracks or on plots of a compaction experiment. The day of measurement was labelled 'after tillage' when the authors in the source publication stated that the measurements had taken place within a few weeks after tillage. Otherwise, it was assumed that the soil had already had time to consolidate before the infiltration measurement was carried out. All soil texture data was mapped onto the USDA classification using the method proposed in Nemes et al. (2001).

Table 6.1: List of new entries added to theJarvis et al. (2013) database.

Reference	Land use	Tillage	Compaction	Sampling time	Data entries
Alagna et al. (2016)	grassland	no tillage	not compacted	consolidated soil	1
Alletto et al. (2015)	arable	conventional tillage	unknown	consolidated soil	60
Bagarello et al. (2014)	arable	no tillage, conventional tillage	unknown	unknown	10
Baranian Kabir et al. (2020)	grassland, arable	no tillage	not compacted, compacted	unknown, consolidated soil	4
Báťková et al. (2020)	arable	reduced tillage, no tillage, conventional tillage	unknown	consolidated soil, soon after tillage	12
Bodner et al. (2013)	arable	no tillage	unknown	soon after tillage, consolidated soil	12
Bottinelli et al. (2013)	arable	unknown, conventional tillage, reduced tillage, no tillage	unknown	consolidated soil	10
Costa et al. (2015)	arable	conventional tillage, reduced tillage, no tillage	not compacted	consolidated soil	3
De Boever et al. (2016)	grassland	no tillage	not compacted	unknown	6
Tóth et al. (2015)	arable	conventional tillage	not compacted, compacted	consolidated soil	2
Fashi et al. (2019)	arable	no tillage, reduced tillage, conventional tillage	compacted, not compacted	unknown	8
Fasinmirin et al. (2018)	arable, woodland / plantation, grassland	conventional tillage, no tillage	not compacted, compacted	unknown	3
Greenwood (2017)	arable, grassland	conventional tillage, no tillage	unknown	consolidated soil	4
Hallam et al. (2020)	arable	conventional tillage	not compacted	unknown	60
Hardie et al. (2012)	arable	no tillage	not compacted	consolidated soil	2
Holden et al. (2014)	grassland	no tillage	not compacted	consolidated soil	5
Hyväluoma et al. (2020a)	arable	conventional tillage	unknown	consolidated soil	4
Iovino et al. (2016)	arable, grassland, woodland/orchard	reduced tillage, no tillage	unknown	consolidated soil	3
Kelishadi et al. (2014)	arable, grassland	reduced tillage, no tillage, conventional tillage	not compacted	consolidated soil	4
Keskinen et al. (2019)	arable	no tillage, conventional tillage	unknown	consolidated soil	15

Table 6.1 – *Continued from previous page*

Reference	Land use	Tillage	Compaction	Sampling time	Data entries
Khetdan et al. (2017)	arable	no tillage	unknown	unknown	4
Larsbo et al. (2016)	arable	conventional tillage	not compacted, compacted	consolidated soil, unknown	5
Lopes et al. (2020)	woodland / orchard, grassland	no tillage	not compacted	consolidated soil	4
Lozano et al. (2014)	arable	no tillage	not compacted	consolidatedsoil	2
Lozano-Baez et al. (2020)	grassland, woodland/orchard	no tillage	not compacted	unknown	18
Matula et al. (2015)	grassland	no tillage	unknown	unknown	3
Miller et al. (2018)	arable	conventional, tillage	unknown	consolidated soil	10
Mirzavand (2016)	arable	conventional, tillage, reduced tillage, no tillage	unknown	consolidated soil	12
Pulido Moncada et al. (2014)	arable, grassland	conventional tillage, no tillage	unknown	unknown	4
Rahbeh (2019)	arable	conventional tillage	unknown	consolidated soil	69
Rienzner and Gandolfi (2014)	arable	conventional tillage	not compacted	unknown, consolidated soil	18
Sandin et al. (2017)	arable	conventional tillage	not compacted, compacted	consolidated soil, unknown	7
Soracco et al. (2015)	grassland	conventional tillage	not compacted, compacted	unknown	3
Soracco et al. (2019)	arable	conventional tillage, no tillage	unknown	consolidated soil	6
Wang (2022)	arable	conventional tillage	unknown	soon after tillage | consolidated soil	25
Wanniarachchi et al. (2019)	arable	conventional tillage	unknown	consolidated soil	6
Yu et al. (2014)	grassland	no tillage	unknown	unknown	11
Yusuf et al. (2018)	arable	no tillage	not compacted	consolidated soil	1
Yusuf et al. (2020)	arable	no tillage	not compacted	consolidated soil	5
Zeng et al. (2013a)	woodland/orchard	conventional tillage	unknown	consolidated soil	20
Zeng et al. (2013b)	grassland	no tillage	unknown	consolidated soil	6
Zhang et al. (2013)	grassland, arable	no tillage, unknown	unknown	consolidated soil	6

Table 6.1 – *Continued from previous page*

Reference	**Land use**	**Tillage**	**Compaction**	**Sampling time**	**Data entries**
Zhang et al. (2014)	arable	conventional tillage	unknown	consolidated soil	4
Zhang et al. (2016)	woodland / orchard, arable	no tillage, conventional tillage	unknown, not compacted	consolidated soil, soon after tillage	24
Zhang et al. (2021)	grassland, woodland / orchard, arable	no tillage, conventional tillage	unknown	consolidated soil	4
Zhao et al. (2014)	arable, grassland	conventional, tillage, no tillage	not compacted	unknown	12
Zhou et al. (2016)	arable, grassland, woodland / orchard	conventional tillage, no tillage	not compacted	soon after tillage	3

6.3.2 Climate data and soil classification

The climatic data entries provided in the database were created using the bioclimatic raster data (BioClim) provided by WorldClim (worldclim.org). The data was averaged across the years 1970 to 2000 and had a 30 arc second resolution (~1 km2; Fick and Hijmans (2017)). The available climate variables were mean annual temperature and precipitation, the mean temperature as well as mean precipitation of the warmest, coldest, wettest and driest quarter and month, respectively, the isothermality, the mean diurnal and annual temperature range, the seasonality for temperature and precipitation. Besides the bio-climatic data in WorldClim we included the aridity index as well as the average annual potential evapotranspiration (ET0). Both were inferred from the "Global Aridity Index and Potential Evapotranspiration Climate Database v2" that is based on the WorldClim database Trabucco and Zomer (2019). The World Reference Base (WRB) soil type was also extracted from the source publications. When it was not reported, the SoilGrids database by ISRIC (de Sousa et al., 2020) was used to infer it. The map contained information about the main soil type regarding the WRB classes (IUSS Working Group WRB, 2015). The most probable soil type was chosen for each location. For all discussed climate and soil maps, the python package "rasterio" (v1.2.10) was used to collect the variables from the corresponding raster cell at the location coordinates given in the source publications.

6.3.3 Model fit to infer to K_h at near-saturated tensions not measured

Tension-disk infiltrometers measure infiltration rates at a specific supply tension (Angulo-Jaramillo et al., 2000) that are then commonly converted to hydraulic conductivities with the aid of the Wooding equation (Wooding, 1968). Note that tension-disk infiltrometers cannot provide measurements at a tension of zero, i.e. K_s. Albeit many publications report K_s values obtained from tension-disk infiltrometers, these measurements must have been conducted at tensions slightly larger than zero, as otherwise water will freely leak out of the tension disk. For this reason, we set the tensions for K_s measurements to 1 mm, but will still refer to these data as saturated hydraulic conductivity. Following Jarvis et al. (2013), we interpolated K_h for tensions in-between the ones measured in the source publications. We achieved this by fitting a log-log linear model with a kink at a tension *hmin*, which denotes the tension at which the largest effective pores in the soil are water-filled (see Figure 6.1). Therefore, K_h == K_s for all tensions h h_{min}.

If K_s was not measured but instead a K_h value at h 5 mm was available, K_s was set to the available K_h value (Figure 6.1 orange line). In cases where more than one K_h value was measured at a tension smaller or equal to 5 mm (including h = 0 mm, i.e. K_s), we averaged them and set K_s and K_h for h h_{min} to the average (Figure 6.1 green line). K_h values at h >5 mm were used to fit the log-log linear relationship. The tension at which the fitted log-log slope intersected with *Ks* defined *hmin*. We used the fitted model to estimate all K_h values for tensions for 10 h 100 mm at 10 mm intervals. The K_h values were only interpolated between the tensions that were measured in the source publication. The only exceptions from this rule were made in the case where a K value for a tension of 80 or 90 mm was provided together with at least one other K value measured at a smaller tension. Then, the missing K values were extrapolated up to a tension of 100 mm. Figure 6.1 shows examples of model fits. Only entries with an R^2 greater or equal to 0.9 are retained in the analysis.

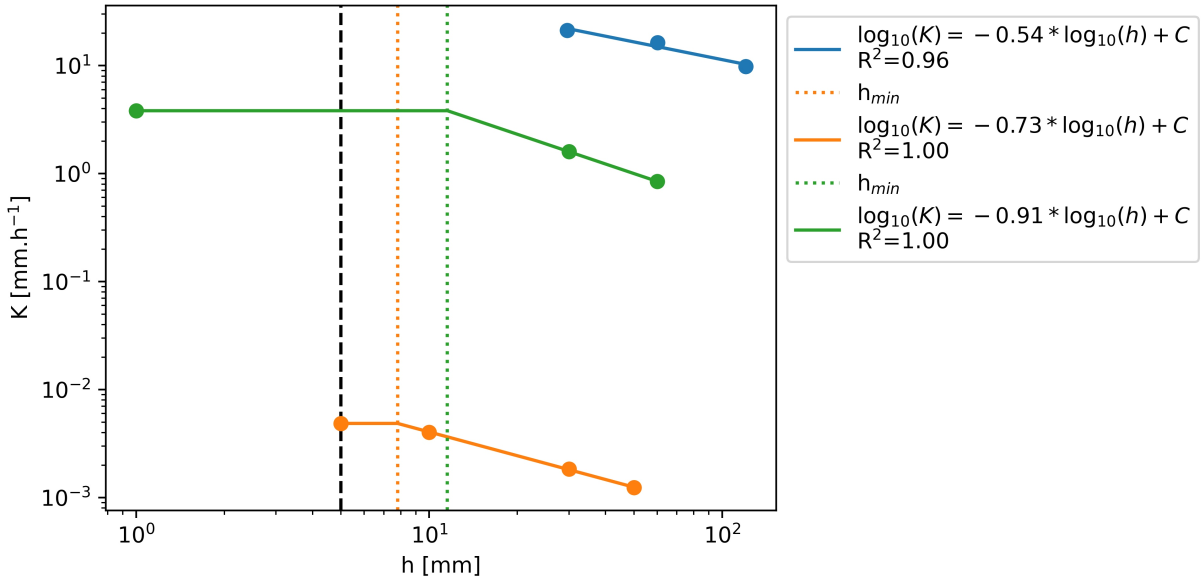


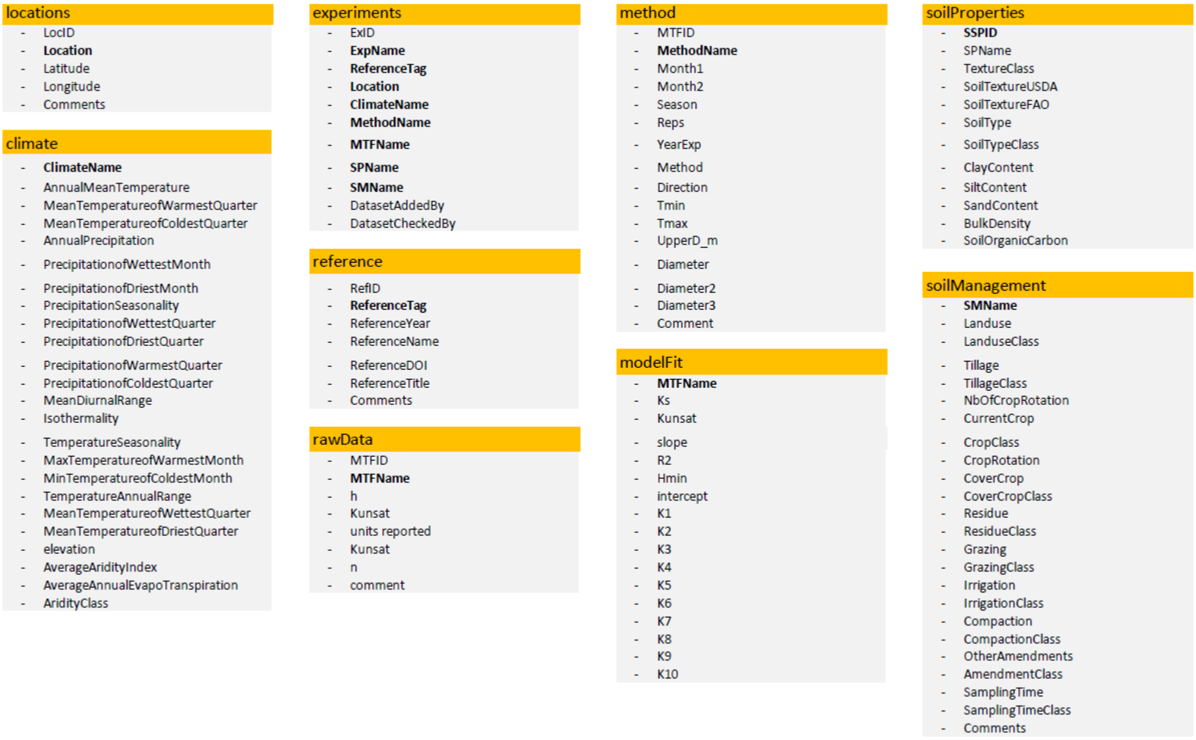
Figure 6.1: Example of linear fit in log-space. K_s values were assigned a tension of 1 mm for illustration purposes. The equations for the linear part of the fit are shown in the legend. C represents the intercept with the y-axis of the linear fit in log-space.

6.3.4 Database organisation

OTIM-DB is organised in 9 individual tables illustrated in Figure 6.2. The main table is named *experiments*. It contains identifiers with which all the other tables are linked. The identifiers are shown in bold font in Figure 6.2. The *reference* table contains information on the references for each study. The *location* table lists the coordinates of the measurement sites. The tables *soilProperties*, *soilManagement* and *climate* store data as implied by their names. The *method* table gives details on the specifications of the tension-disk infiltrometer and the method to calculate hydraulic conductivity from the infiltration rate. The *rawData* table contains the hydraulic conductivities and respective supply tensions as stated in the corresponding source publication. Note that OTIM-DB does not contain raw data for the entries of the original version compiled for Jarvis et al. (2013). Finally, *modelFit* reports K_h for 0 h 100 mm as described above. For more details, the reader is directed to the 'description' tab of the database (not shown in Figure 6.2) where the meanings and units of each column are explained.

6.3.5 Data availability and coverage

Although 92% of the data in OTIM-DB was obtained from measurements on the topsoil, it also contains some data points measured at greater soil depths. In the following meta-analysis, only measurements from the topsoil were included and all datasets measured at soil depths below 300 mm were removed. Also, all data entries were discarded for which the log-log linear model could not be fitted with a coefficient of determination of 0.9 or better. Last but not least, we found that the relationship between supply tension and K_h was distorted if data entries were included that did not cover the complete tension range from h = 0 to 100 mm. Possible reasons for the difficulties to match K_h data from tension series with different lengths are discussed at the beginning of the



locations
- LocID
- **Location**
- Latitude
- Longitude
- Comments

climate
- **ClimateName**
- AnnualMeanTemperature
- MeanTemperatureofWarmestQuarter
- MeanTemperatureofColdestQuarter
- AnnualPrecipitation
- PrecipitationofWettestMonth
- PrecipitationofDriestMonth
- PrecipitationSeasonality
- PrecipitationofWettestQuarter
- PrecipitationofDriestQuarter
- PrecipitationofWarmestQuarter
- PrecipitationofColdestQuarter
- MeanDiurnalRange
- Isothermality
- TemperatureSeasonality
- MaxTemperatureofWarmestMonth
- MinTemperatureofColdestMonth
- TemperatureAnnualRange
- MeanTemperatureofWettestQuarter
- MeanTemperatureofDriestQuarter
- elevation
- AverageAridityIndex
- AverageAnnualEvapoTranspiration
- AridityClass

experiments
- ExID
- **ExpName**
- **ReferenceTag**
- **Location**
- **ClimateName**
- **MethodName**
- **MTFName**
- **SPName**
- **SMName**
- DatasetAddedBy
- DatasetCheckedBy

reference
- RefID
- **ReferenceTag**
- ReferenceYear
- ReferenceName
- ReferenceDOI
- ReferenceTitle
- Comments

rawData
- MTFID
- **MTFName**
- h
- Kunsat
- units reported
- Kunsat
- n
- comment

method
- MTFID
- **MethodName**
- Month1
- Month2
- Season
- Reps
- YearExp
- Method
- Direction
- Tmin
- Tmax
- UpperD_m
- Diameter
- Diameter2
- Diameter3
- Comment

modelFit
- **MTFName**
- Ks
- Kunsat
- slope
- R2
- Hmin
- intercept
- K1
- K2
- K3
- K4
- K5
- K6
- K7
- K8
- K9
- K10

soilProperties
- **SSPID**
- SPName
- TextureClass
- SoilTextureUSDA
- SoilTextureFAO
- SoilType
- SoilTypeClass
- ClayContent
- SiltContent
- SandContent
- BulkDensity
- SoilOrganicCarbon

soilManagement
- **SMName**
- Landuse
- LanduseClass
- Tillage
- TillageClass
- NbOfCropRotation
- CurrentCrop
- CropClass
- CropRotation
- CoverCrop
- CoverCropClass
- Residue
- ResidueClass
- Grazing
- GrazingClass
- Irrigation
- IrrigationClass
- Compaction
- CompactionClass
- OtherAmendments
- AmendmentClass
- SamplingTime
- SamplingTimeClass
- Comments

Figure 6.2: Structure of the OTIM-DB database with its different tables and columns. In the *soil-Management* table, the columns with the suffix “Class” denote columns in which the data reported in the source publications were summarised into classes to facilitate comparing them. For example, the reported *CurrentCrop* like wheat, rye, barley or oat was assigned the *CropClass* cereals. The rows **in bold** denote unique identifiers with which the table entries are linked to the *experiments* table.

results and discussion section. Except for this discussion, we focused on data entries that included K_h values for the complete tension range in the exploratory data analysis and the meta-analyses. The available datasets after these filtering steps correspond to the ones indicated in blue ('focus') in the following figures.

Figure 6.3 shows the number of publications included in the OTIM-DB per publication year. On average, 6.7 new publications per year were published after 2000.

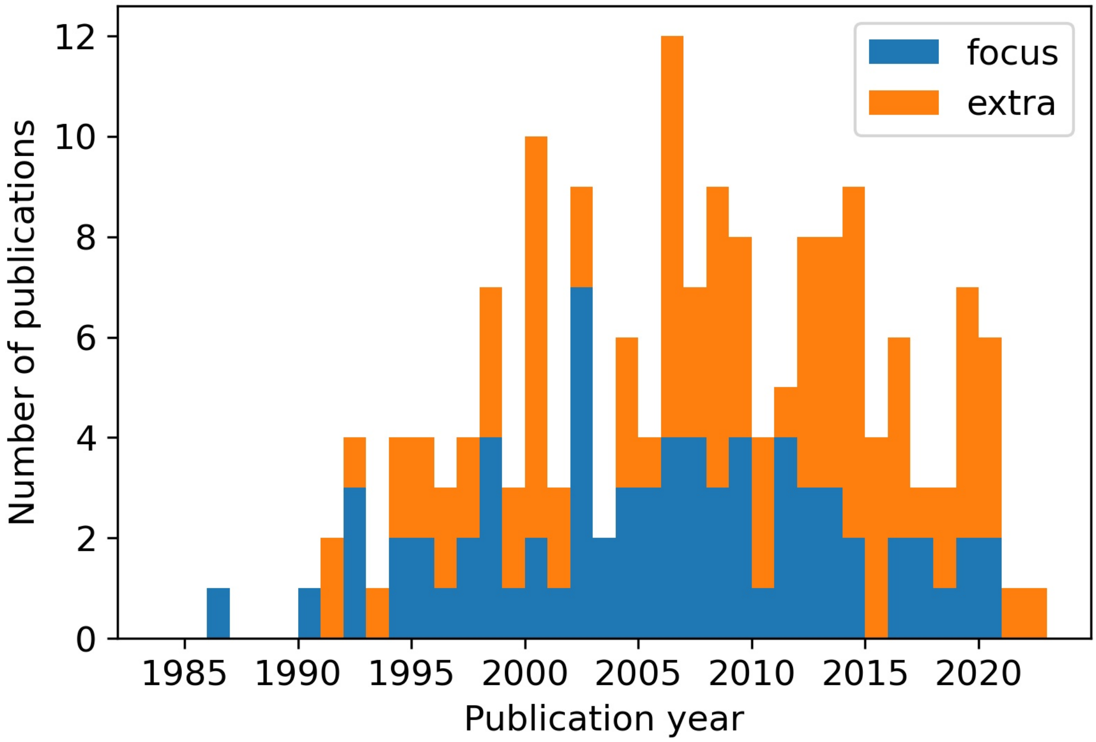


Figure 6.3: Distribution of the publication year in the OTIM-DB. Publications labelled as 'focus' contain K_h for all tensions between h = 0 and 100 mm, were measured at soil depths of less than 20 mm and exhibited coefficients of determination for the log-log linear model fit of 0.9 or more. Publications denoted as 'extra' predominantly miss either data at the wet or the dry range (or both), were obtained from the subsoil or could not be well fitted with the log-log linear model.

Most tension-disk infiltrometer studies were conducted in Europe, North America and Western Australia (Figure 6.4). Clearly, fewer studies have been carried out in Asia, South America and Africa. The lack of datasets from Russia, Mesoamerica, the arctic regions and the tropics is remarkable. This geographical bias is aggravated if only measurements on the topsoil are considered that allow inferences about K_h for the complete range of tensions (0 h 100 mm) with a sufficiently good coefficient of determination. Then, all the data entries collected in southern South America and South-western Australia would need to be omitted. In this respect, the OTIM-DB database is biassed towards ecosystems in temperate climate regions.

Figure 6.5 depicts the number of K_h values available for 0 h 100 mm. These figures represent the hydraulic conductivities derived from the log-log linear model presented above, not the raw data measured and reported in the source publications. While a large number of entries span the full range of tensions of interest (0 to 100 mm), there are fewer entries that have data up to a tension of 60 mm. Often, but not always, such data series were obtained with the widely available Mini-Disk

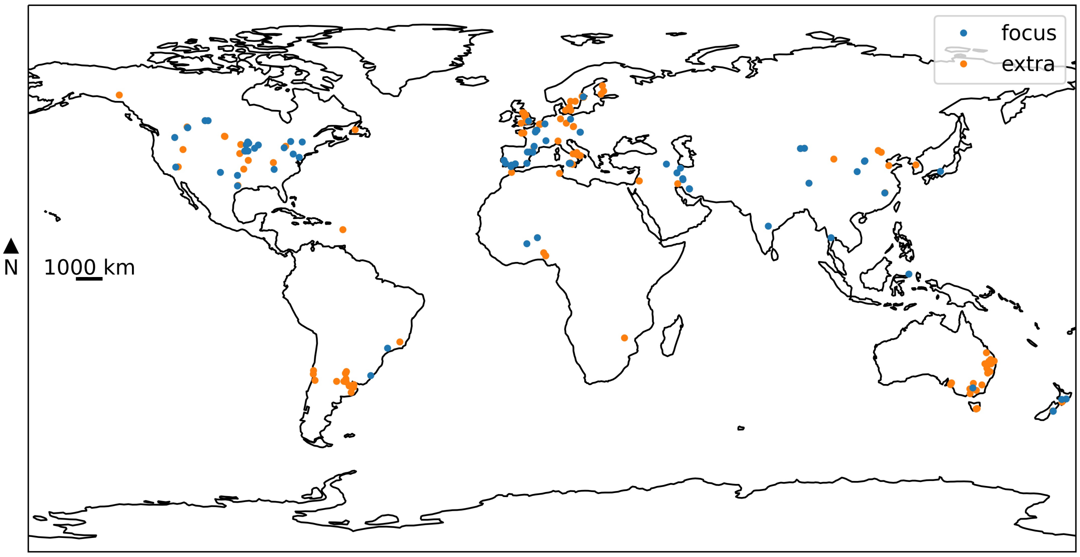


Figure 6.4: Map of the study locations collected in the OTIM-DB. See caption to Figure 6.3 for the definition of ‘focus’ and ‘extra’ locations.

infiltrometer distributed by the *Meter* group (formerly by *Decagon*), which is limited to tensions h 70 mm.

An overview on the metadata included in OTIM-DB is given in Table 6.2. Data gaps are present, especially for bulk density and for information on the soil management at the study site except for tillage operations. Note that the annual mean temperature and precipitation are only two examples representing the climatic variables enumerated in section 2.3. There are very few missing values for the climate data, since it was estimated from the coordinates of the study sites. The same holds for the elevation data and information on the WRB soil type.

6.4 Meta-analyses

6.4.1 Methods

Exploratory data analysis

Some source publications only provided a few data entries for K_h, sometimes only comparing two different treatments, while other source studies contain data for a larger number of treatments and/or sites. In some publications, data for all individual tension-disk measurements are available, even if replicates were measured. In others, only averages of the replicated measurements are reported, while still others yield average K_h values for individual replicated treatment blocks. This

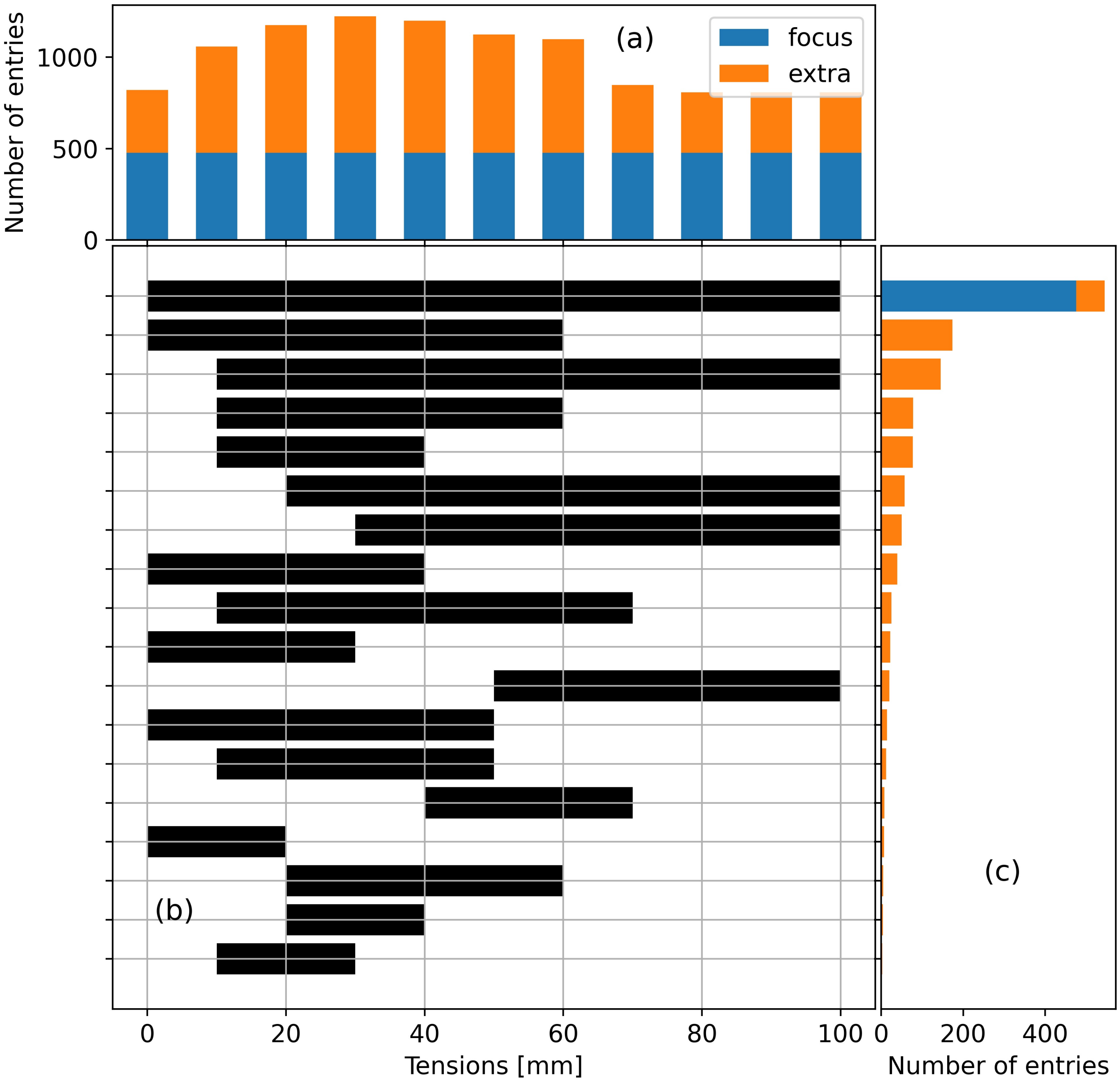


Figure 6.5: (a) number of available K_h values per supply tension, (b) range of available tensions and (c) their respective occurrence in the database.

Table 6.2: Number of entries and gaps for each feature along with units and range (if continuous) or choices (if categorical). The values are shown for the filtered entries ('focus') and in parenthesis for all the entries available in the database ('focus' and 'extra').

Type	Predictor	Unit	Range	Number of entries	Number of gaps
Soil	Sand content	kg.kg-1	0.0 ->0.9 (0.0 ->1.0)	369 (1070)	40 (215)
Soil	Silt content	kg.kg-1	0.0 ->0.8 (0.0 ->0.8)	369 (1070)	40 (215)
Soil	Clay content	kg.kg-1	0.0 ->0.7 (0.0 ->0.8)	372 (1107)	37 (178)
Soil	Bulk density	g.cm-3	0.5 ->1.8 (0.1 ->2.2)	302 (771)	107 (514)
Soil	Soil organic carbon	kg.kg-1	0.0 ->1.0 (0.0 ->1.0)	320 (938)	89 (347)
Climate	Annual mean temperature	°C	-3.8 ->27.9 (-3.8 ->29.1)	409 (1214)	0 (71)
Climate	Annual mean precipitation	mm	22.0 ->3183.0 (22.0 ->3183.0)	409 (1214)	0 (71)
Climate	Average aridity index	-	0.0 ->1.9 (0.0 ->2.8)	409 (1214)	0 (71)
Climate	Precipitation seasonality (CV)	-	9.9 ->111.2 (9.6 ->138.5)	409 (1214)	0 (71)
Climate	Mean diurnal range	°C	6.9 ->18.2 (4.8 ->18.5)	409 (1214)	0 (71)
Management	Land use	choices	arable, bare, grassland, woodland/orchard	396 (1249)	13 (36)
Management	Tillage	choices	conventional tillage, no tillage, reduced tillage	384 (1190)	25 (95)
Management	Soil compaction	choices	compacted, not compacted	62 (265)	347 (1020)
Management	Sampling time	choices	after tillage, consolidated soil	324 (993)	85 (292)

makes appropriate data weighting complicated, but also extremely important when analysing the meta-dataset. It also introduces uncertainty, because it is not always clear whether the replicated averages were calculated using the geometric or the arithmetic mean. Considering that hydraulic conductivities at or near saturation are known to be log-normally distributed, the former would be best. In the following, we assumed that geometric averaging was used when replicated values were reported in source publications. In the following, we calculated data weights as

$$\omega_i = \frac{n_{r,i}}{\sqrt{N_i}} \tag{6.1}$$

where ω_i is the weight for data entry *i*, $n_{r,i}$ is the number of replicates from which the values of *i* were averaged and N_i is the total number of measurements included in the publication from which data entry *i* was obtained. With the above described weights, we up-weight data entries according to the number of replicate measurements from which they were averaged, but down-weight the impact of studies that published larger amounts of data.

The metadata for the datasets used in the exploratory data analysis are summarised in Figure 6.6. The distributions of the climate variables illustrate that the data in OTIM-DB was mostly acquired in temperate climates, with a bias towards drier climates, as already expected from the distribution of the sampling sites shown in Figure 6.4. The soil texture, bulk density and organic carbon content data appear reasonably representative for soils in this climate zone. OTIM-DB contains predominantly data from arable fields.

Effect size computation

Data entries in OTIM-DB with specific land use or management were very unevenly distributed. For example, the large majority of data was measured on sites with land use ‘arable’ (see Figure 6.6a). Such uneven distributions may lead to bias when it is averaged over all entries of a specific feature like it was done in the exploratory data analysis. We therefore investigated the effects of land use and management as well as soil compaction and time of measurement on K_h with the aid of pairwise comparisons published within individual studies and calculated so-called effect sizes (*ES*) for each investigated feature class.

To reduce bias arising from the varying number of data entries published within individual studies, we grouped all entries according to the factors land use, tillage, compaction, and sampling time. Here we only considered binary pairs, that is arable or not arable in the case of land use and tilled or not tilled, compacted or not compacted as well as ‘measured soon after tillage’ or ‘measured on consolidated soil’ for the other three factors. In addition, we checked whether different entries within individual studies stemmed from the same or a very similar site. We did this by comparing the respective USDA texture classes and a climate variable, namely the aridity class. All data entries within an individual study that exhibited identical land use, soil management, compaction, sampling time, texture and aridity were averaged and the number of corresponding replicates was summed.

For each binarized factor (e.g. Tillage), a *control* value was chosen (e.g. zero tillage). All values different from the control represent the *treatment* (e.g. conventional tillage and reduced tillage). Within individual studies, pairs among the averaged entries were formed for each combination of a control and a treatment value. These pairs were used to compute the effect size. Following Basche and DeLonge (2019), we defined the effect sizes as the log10 of the ratio of $K_{h,t}$ of the treatment divided by $K_{h,c}$ of the control

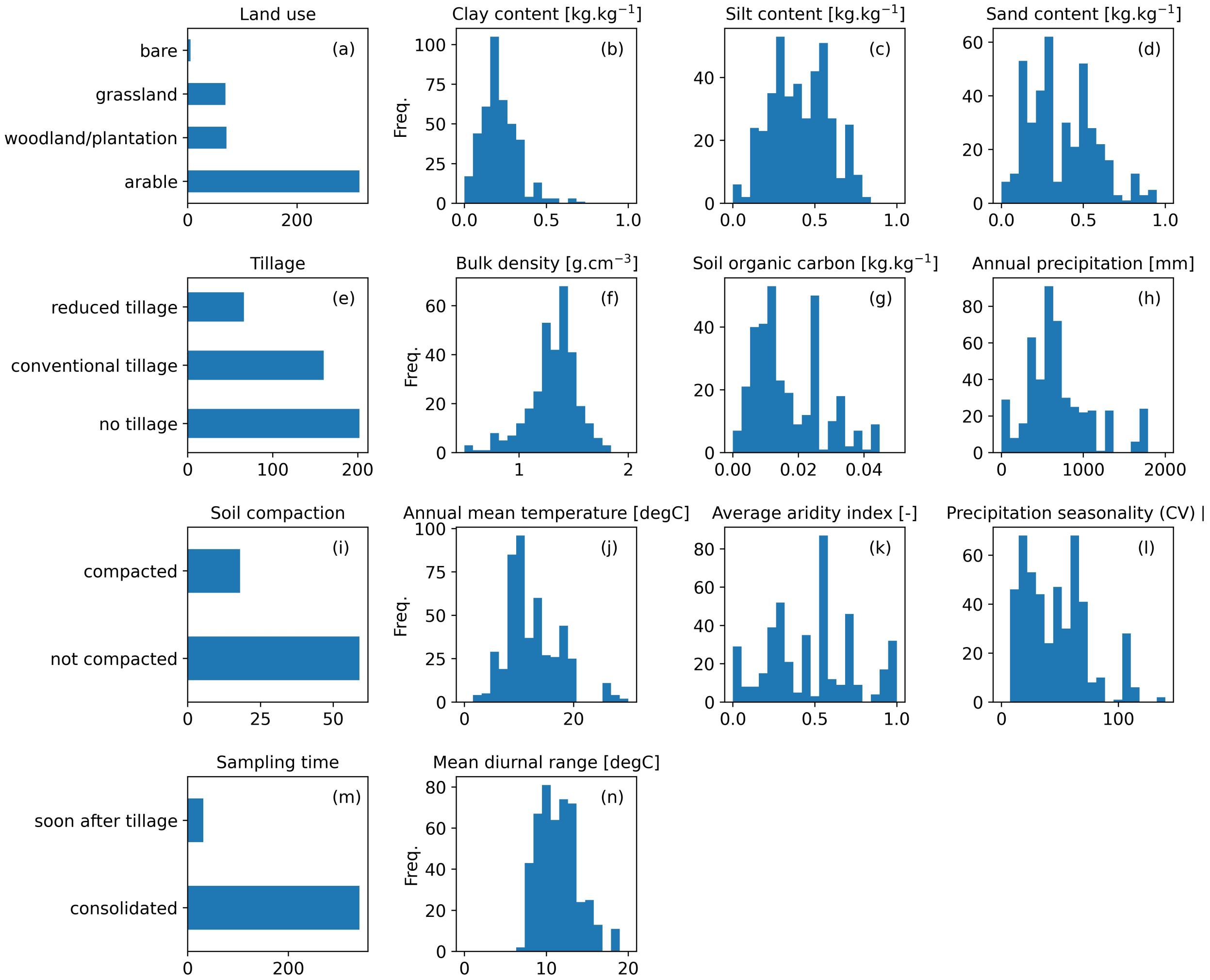


Figure 6.6: Distributions of continuous and categorical variables in the retained dataset.

$$ES_l = \log_{10}\left(\frac{K_{h,t}}{K_{h,c}}\right) \tag{6.2}$$

where the subscript l indicates the *l*th pair for which the effect size was computed and the indices '*t*' and '*c*' stand for treatment and control, respectively. The average effect size *ES* for each of the four investigated factors was calculated as the weighted mean of the individual ES_l using the weight

$$w_l = \frac{v_c v_t}{v_c + v_t} \tag{6.3}$$

where the subscript *l* indicates again the *l*th pair for which the effect size was computed and v_c and v_t denote the number of (summed) replicates for control and treatment, respectively. In addition, we calculated the weighted standard error

$$\sigma_{\bar{ES}} = \sqrt{\frac{\sum_{i=0}^{n} w_l \left(ES_l - \bar{ES}\right)^2}{\frac{n-1}{n}\sum_{l=0}^{n} w_l}} \tag{6.4}$$

where $\bar{ES}$ is the mean effect size.

Table 6.3 summarises the evaluated factors, the number of pairs involved and the number of different studies from which the pairs were obtained.

Table 6.3: Number of studies and paired comparison with their respective control and treatment values used for the meta-analysis of *K10* values.

Factor	**Control**	**Treatments**	**Studies**	**Paired comparisons**
Land use	not arable	arable	10	24
Tillage	no tillage	conventional tillage, reduced tillage	15	32
Compaction	not compacted	compacted	6	8
SamplingTime	consolidated soil	soon after tillage	6	12

To estimate the robustness of the effect size, we carried out a sensitivity analysis using the Jackknife technique, similarly to Basche and DeLonge (2019). This method aims to show the sensitivity of the averaged effect size to data from specific studies. For each factor, a given number of studies was randomly picked and removed from the dataset. The averaged effect size and its standard error was computed with the rest of the dataset. The process started by removing one study, after which up to nine more studies were removed. This random picking was repeated 50 times to rule out bias. The average of the means and standard errors for the 50 realisations was computed and plotted. Observed effect sizes were judged trustworthy, if they did not change after removal of studies to calculate them. We constrained the sensitivity analyses in our study to the effect sizes for K_s and K_{100}.

Publication bias

We planned a publication bias following the procedures summarised in Rothstein et al. (2005). The analytical sequence to be used was: i) the graphical method of contour-enhanced funnel plots, which help to relate asymmetry patterns to statistical significance; ii) the assessment of the small-size effects with the Egger's regression test; iii) the trim and fill method to assess and to correct any asymmetry in the funnel plot; iv) the p-curve method, which focuses on p-values as the main driver of publication bias.

As suggested in the literature, in the application of this sequence we planned to use two threshold values for the implementation of the analytical pathway: the presence of at least ten studies with the required starting information and a heterogeneity value of less than 50% to apply of the trim and fill and the p-curve methods. In the analytical sequence, we instead excluded the application of the Failsafe N method because it ignores the magnitude of the effect, and no statistical criteria were available to aid interpretation.

The information required at the outset for the publication analysis is the value of the effect sizes together with their standard deviations for each of the studies selected in the meta-analysis. Unfortunately, most of the selected publications did not report dispersion statistics in numerical form or in any way derivable from the figures. For example, in the case of the conventional tillage vs. no tillage comparison, only 8 of the 24 studies reported standard deviations of effect sizes, while only two of them reported the standard deviations of the log-transformed values that would be needed to estimate the publication bias as outlined above. Failure to meet this basic requirement prevented us from proceeding in more advanced publication bias analysis.

However, we carried out a simpler approach for the K_{100} data, in which histograms of the response ratios were investigated. Any deviation from a normal distribution indicates publication bias.

6.4.2 Results and discussion

Differences between data entries with different tension ranges

If all data are considered ('focus' and 'extra'), Figure 6.5 illustrates that approximately 40% of the data in OTIM-DB provided K_h for every h with 0 h 100 mm. For another 40%, K_h was only measured in the wet range, i.e. at tensions below 70 mm. The remaining K_h data was only acquired at the dry range. Here, we counted all data entries for which K_s were not measured and could not be estimated. Figure 6.7 illustrates how data from entries with complete, dry and wet ranges differed. The K_h for the wet range receded faster with increasing tension than series that also included measurement in the dry range. A large portion of these datasets were obtained with the Mini-Disk infiltrometer. However, a closer inspection of the impact of the disk diameters used to acquire the respective K_h did not confirm suspicions that the bias was related to the use of this special type of infiltrometer. While the observed differences between the K_h curves could have been introduced by co-correlations with soil texture or climate, other explanations appear more plausible. The vast majority (approximately 86%) of the experiments in OTIM-DB were conducted starting from a high tension and progressively measured at more saturated conditions. It follows that the first measurement of K_h series including large tensions was carried out under drier conditions than the series focusing only on the wetter range of the spectrum, respectively. The larger the supply tension, the longer it takes to acquire a measurement. It may therefore be that any initial water repellency of soils played a major role when the experiments were started under relatively wet conditions, while it was overcome during the first infiltration run under drier conditions. Another potential explanation would be that the steeper K_h recessions with tension for the data series in the wet range were caused when fitting the log-log linear model. If this was the case, it would follow that the log10 K_h to $\log_{10} h$ slope was steeper for smaller than for larger tensions, thus deviating from a linear relationship. Whatever the reason behind this observation, we found that including the data series that are constraint on the wet tension range leads to artefacts in K_h relationship with tension, which take on the form of a kink in between tensions of 60 and 70 mm. Note that similar kinks were when mixing data from data entries for which K_h had only been measured at the dry end of the considered tension range. Also already discussed, we focused solely on data entries for which we were able to reconstruct K_h for all h in between 0 and 100 mm supply tension in the following exploratory data analyses and meta-analyses. This greatly facilitated the data interpretation.

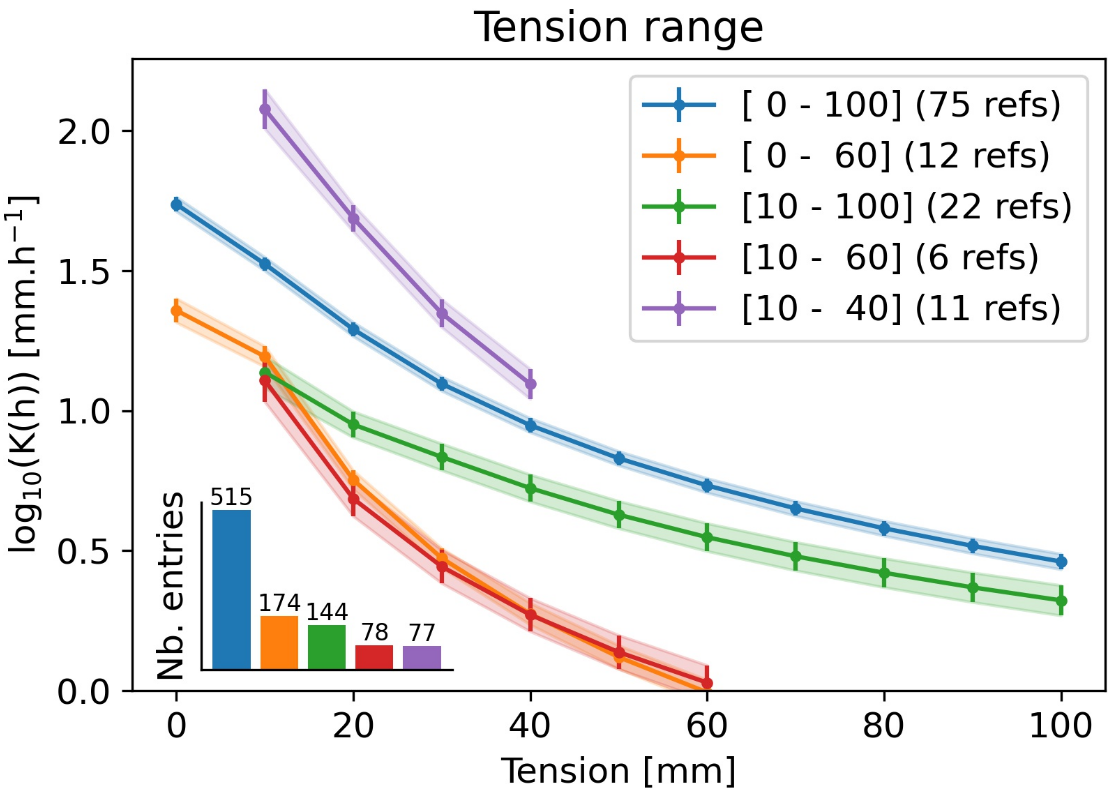


Figure 6.7: Evolution of weighted mean K_h with tension available in OTIM-DB, sorted by the tension range the data was spanning. The number of publications from which the data originated is shown between parentheses in the legend. The shaded areas and the error bars represent the weighted standard error of the mean.

Statistical relationships between K_h and methods used

Figure 6.8a confirms that the diameter of the tension disk did not have a systematic impact on the results. The majority of the data were collected starting under dry conditions (large tensions) and subsequently measured under increasingly wet conditions (smaller tensions). Figure 6.8b illustrates that beginning the experiment under wet conditions is associated with larger water contents and hydraulic conductivities at identical supply tensions. This is well known and referred to hysteresis, which is due to ink bottle effects, impacts of water repellency, air entrapment and swelling of clay particles (Hillel, 2003). Figure 6.8c shows that the large majority of studies used the 'steady-state piecewise' method to solve the Wooding equation and convert the measured infiltration rates to hydraulic conductivities. This method leads to smaller K_h for larger tensions than the other methods. The 'transient' and 'steady-state constant' methods yielded larger K_h in the unsaturated range. For the latter method, it is known that it overestimates unsaturated K_h (Jarvis et al., 2013). We tested whether excluding data from 'transient' and 'steady-state constant' methods changed the results of the meta-analyses, but found that they only changed to a minor degree. Data from all methods were therefore included in the following. Note that the 'transient' method was mostly applied in conjunction with Mini-Disk Infiltrometers, albeit the respective data is not included in Figure 6.8 since it does not span the entire suction range.

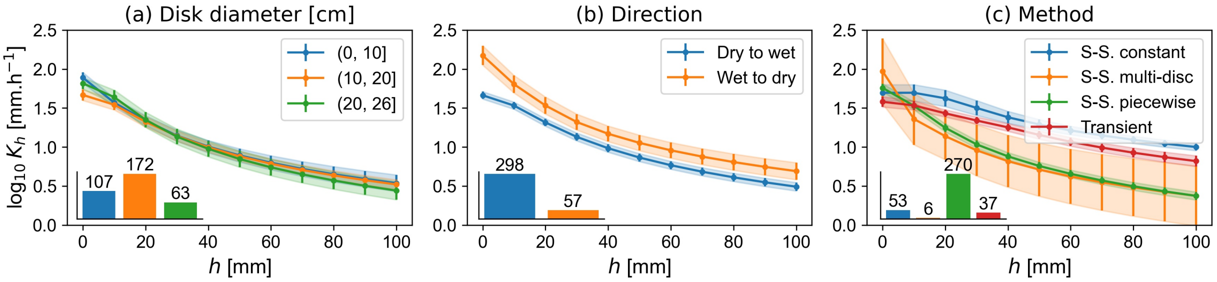


Figure 6.8: Evolution of weighted mean K_h as a function of applied tension for (a) disk diameter, (b) direction and (c) method of fitting. 'S.-S.' stands for 'steady-state'. More specifically, the method 'S.-S. constant' is outlined in Logsdon and Jaynes (1993), 'S.-S. multi-disc' in Smettem and Clothier (1989), and 'S.-S. piece-wise' in Reynolds and Elrick (1991) or Ankeny et al. (1991) and 'Transient' in Zhang (1997) or Vandervaere et al. (2000). The shaded areas and the error bars represent the weighted standard error of the mean.

Correlations between K_h at different saturations

Figure 6.9 illustrates that K_s was clearly different from K_h in the near-saturated range. Already K_{10} was better correlated with K_{20} than with K_s. This indicates that K_s results from fundamentally different flow paths than K_h at 20 mm supply tension or drier. The flow paths at saturation reflect the largest connected macropores. Also air entrapment may play a role here. It may alter the relationship between pore-network morphology and water-flow paths and therefore further decouple K_s from proxies describing the pore-network. Figure 6.9 also shows that K_h was strongly correlated in the range between 40 and 100 mm tensions. This indicates that flow paths did not dramatically change with tension at the dry end of the investigated tension range.

Statistical relationships between K_h and soil properties

Soils with coarse texture exhibited larger K_h in the unsaturated range, which is caused by the large and abundant primary pores in between individual sand grains (Figure 6.10a). At saturation, the hydraulic conductivity of all three texture classes was approximately identical. This is explained by the presence of large structural pores in the medium and fine-textured soils. Medium-textured soils had the lowest K_h in the investigated range of tensions, which may be due to a denser soil matrix in loamy soils and a lower structural stability of silty soils. Larger bulk densities decreased K_h across

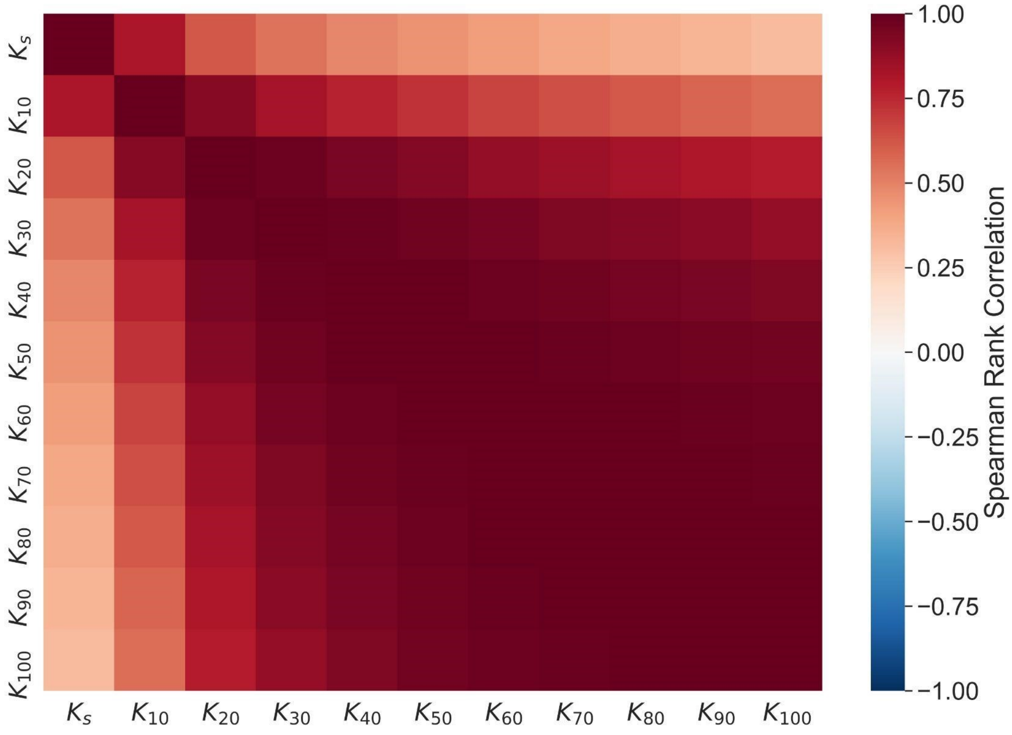


Figure 6.9: Spearman rank correlation coefficients between K_h at different tensions.

the whole range of investigated tensions, which reflects the reduced porosity with increasing bulk density (Figure 6.10b). The hydraulic conductivity in the saturated and near-saturated range is especially affected by soil compaction, which predominantly reduces the abundance and connectivity of macropores (Pagliai et al., 2004; Whalley et al., 1995). Large bulk densities are also known to reduce burrowing activities of the soil macrofauna (Capowiez et al., 2021) as well as root growth (Lipiec and Hatano, 2003), also leading to less abundant and less connected large macropores. The soil organic carbon content was connected with smaller K_h at the dry end of the investigated tension range if soils with organic carbon contents of more than 0.03 kg.kg^{-1} were excluded (Figure 6.10c). This decrease may be explained by water repellency, which is generally positively correlated with organic carbon content. A similar observation was already reported in Jarvis et al. (2013). Note that correlations of SOC with soil texture were not observed in the investigated dataset (Figure 6.11).For soils with organic carbon contents larger than 0.03 kg.kg^{-1}, K_h increased once again. This may indicate that, above this threshold, better developed macropore networks associated with large SOC contents (e.g. Larsbo et al. (2016)) outweighed any effects of water repellency.

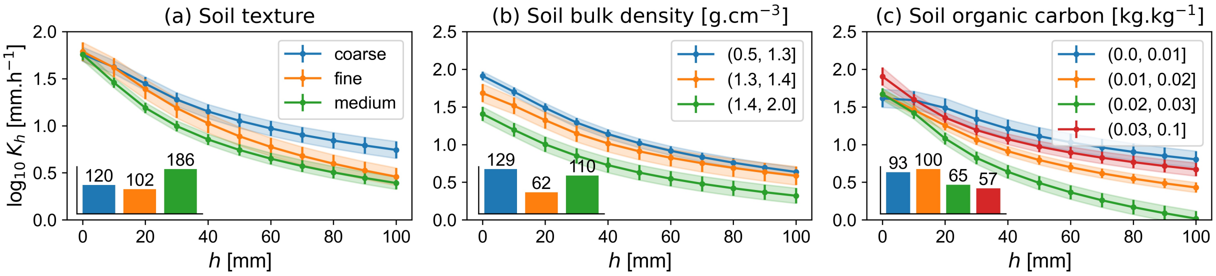
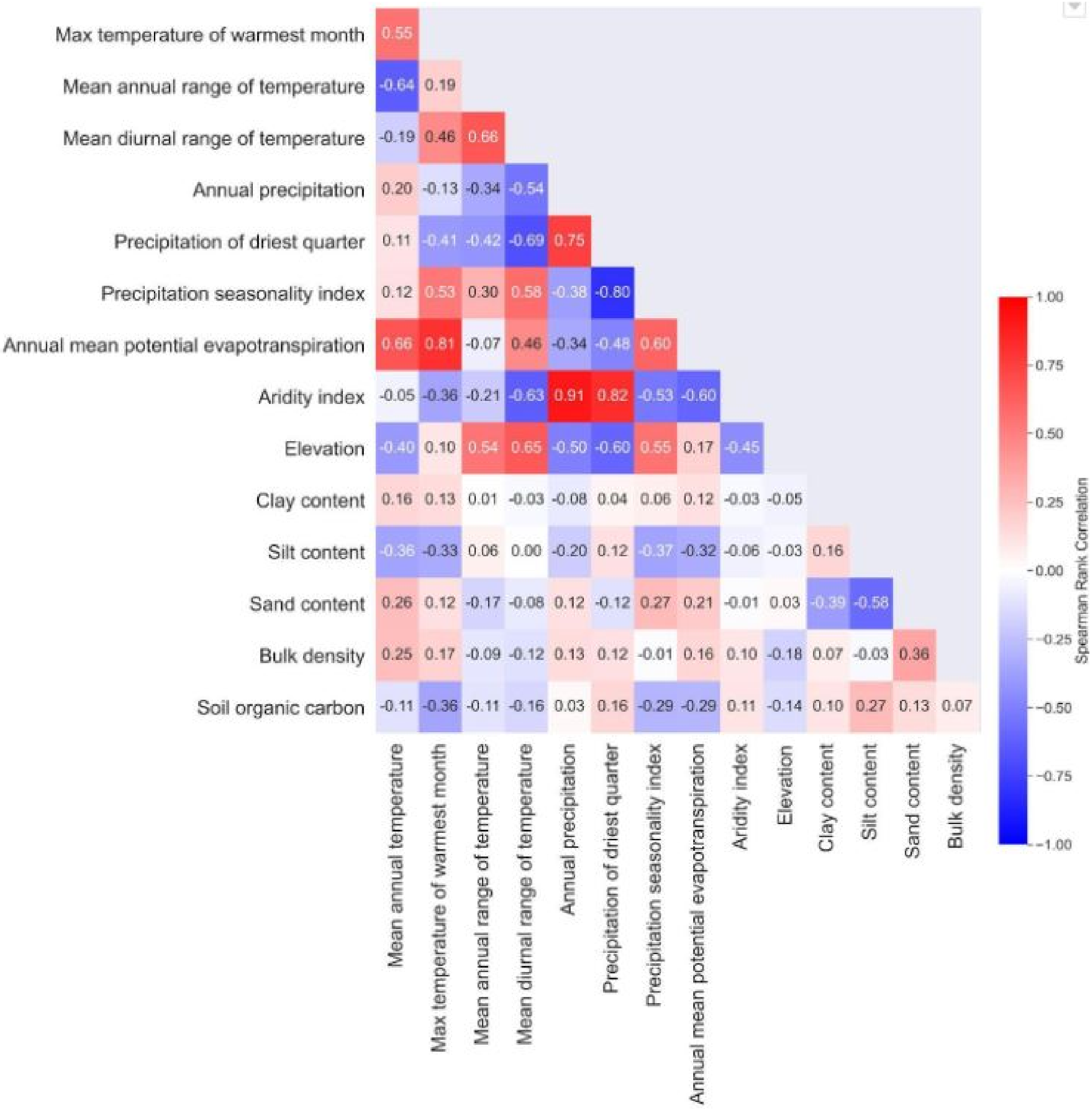


Figure 6.10: Evolution of weighted mean K_h as a function of applied tension for (a) soil texture, (b) soil bulk density and (c) soil organic carbon. The shaded areas and the error bars represent the weighted standard error of the mean. The soil textures were classified using USDA texture classes as follows: fine (clay, clay loam, silty clay, silty clay loam), medium (silt loam, loam), coarse (loamy sand, sand, sandy clay, sandy clay loam, sandy loam).

Statistical relationships between K_h and climate variables

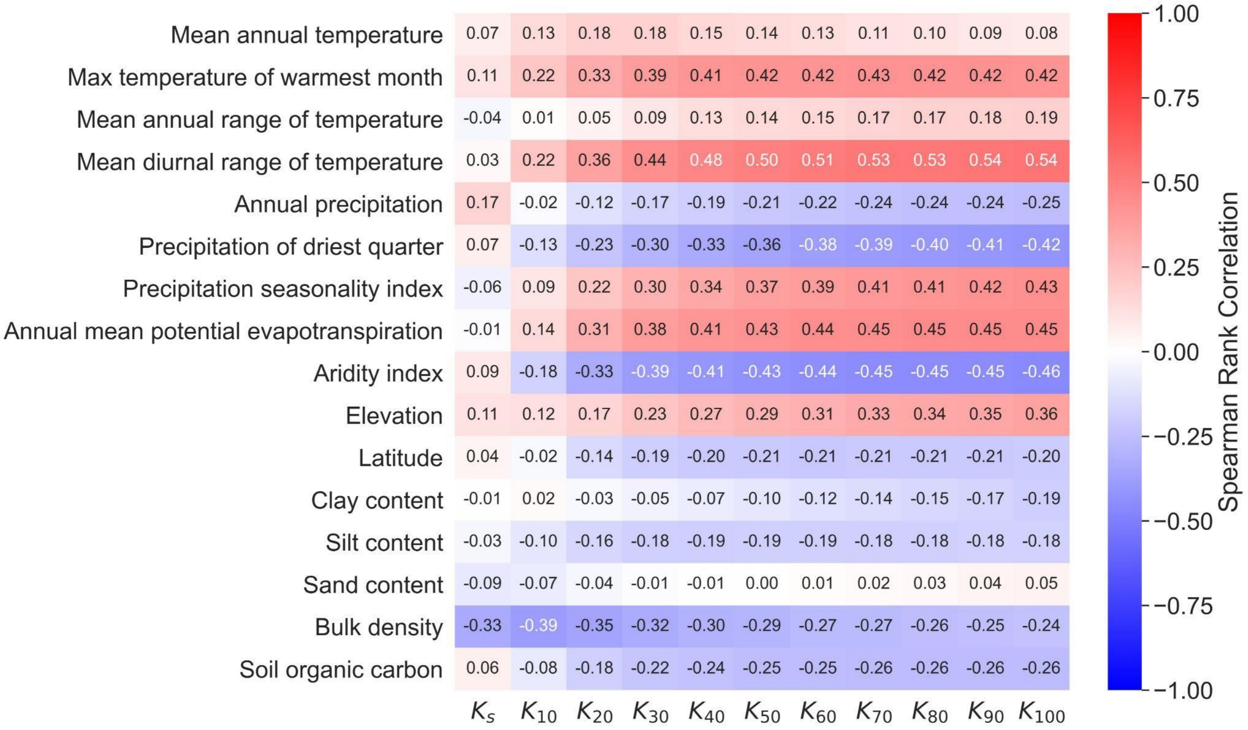
One of the important observations made in recent years was that saturated and near-saturated hydraulic conductivities are strongly correlated with climate variables (Jarvis et al., 2013; Jorda et al., 2015; Hirmas et al., 2018). Figure 6.11 gives an overview over weighted Spearman rank correlations between K_h and nine of the 20 climate variables included in OTIM-DB that exhibited the strongest correlations with K_h. The elevation of the sampling site above sea level, its latitude and the values for soil texture, bulk density and soil organic carbon content are also shown for comparison. It is striking that the soil properties were clearly less well correlated with K_h than some of the climate variables. The largest absolute values of the weighted rank correlations were observed for the mean diurnal range of temperature and the aridity index. Both reach a maximum at the dry end of the considered tension range, i.e. for K_{10}, with correlation coefficients of 0.54 and -0.47, respectively. The strength of these correlations was reduced with smaller tensions to values close to zero at K_s (Figure 6.12). The loss of correlation occurred rather abruptly at supply tensions between 10 and 20 mm, again pointing at a threshold above which different kinds of pores and/or air entrapment may become important for water transport.

It should be noted that both variables, the annual mean diurnal temperature range and the aridity index, were strongly correlated with each other, with a weighted correlation coefficient of 0.67 (Fig-



	Mean annual temperature	Max temperature of warmest month	Mean annual range of temperature	Mean diurnal range of temperature	Annual precipitation	Precipitation of driest quarter	Precipitation seasonality index	Annual mean potential evapotranspiration	Aridity index	Elevation	Clay content	Silt content	Sand content	Bulk density
Max temperature of warmest month	0.55													
Mean annual range of temperature	-0.64	0.19												
Mean diurnal range of temperature	-0.19	0.46	0.66											
Annual precipitation	0.20	-0.13	-0.34	-0.54										
Precipitation of driest quarter	0.11	-0.41	-0.42	-0.69	0.75									
Precipitation seasonality index	0.12	0.53	0.30	0.58	-0.38	-0.80								
Annual mean potential evapotranspiration	0.66	0.81	-0.07	0.46	-0.34	-0.48	0.60							
Aridity index	-0.05	-0.36	-0.21	-0.63	0.91	0.82	-0.53	-0.60						
Elevation	-0.40	0.10	0.54	0.65	-0.50	-0.60	0.55	0.17	-0.45					
Clay content	0.16	0.13	0.01	-0.03	-0.08	0.04	0.06	0.12	-0.03	-0.05				
Silt content	-0.36	-0.33	0.06	0.00	-0.20	0.12	-0.37	-0.32	-0.06	-0.03	0.16			
Sand content	0.26	0.12	-0.17	-0.08	0.12	-0.12	0.27	0.21	-0.01	0.03	-0.39	-0.58		
Bulk density	0.25	0.17	-0.09	-0.12	0.13	0.12	-0.01	0.16	0.10	-0.18	0.07	-0.03	0.36	
Soil organic carbon	-0.11	-0.36	-0.11	-0.16	0.03	0.16	-0.29	-0.29	0.11	-0.14	0.10	0.27	0.13	0.07

Figure 6.11: Weighted Spearman rank correlation coefficients between climate variables, elevation above sea level and soil properties.



	K_s	K_{10}	K_{20}	K_{30}	K_{40}	K_{50}	K_{60}	K_{70}	K_{80}	K_{90}	K_{100}
Mean annual temperature	0.07	0.13	0.18	0.18	0.15	0.14	0.13	0.11	0.10	0.09	0.08
Max temperature of warmest month	0.11	0.22	0.33	0.39	0.41	0.42	0.42	0.43	0.42	0.42	0.42
Mean annual range of temperature	-0.04	0.01	0.05	0.09	0.13	0.14	0.15	0.17	0.17	0.18	0.19
Mean diurnal range of temperature	0.03	0.22	0.36	0.44	0.48	0.50	0.51	0.53	0.53	0.54	0.54
Annual precipitation	0.17	-0.02	-0.12	-0.17	-0.19	-0.21	-0.22	-0.24	-0.24	-0.24	-0.25
Precipitation of driest quarter	0.07	-0.13	-0.23	-0.30	-0.33	-0.36	-0.38	-0.39	-0.40	-0.41	-0.42
Precipitation seasonality index	-0.06	0.09	0.22	0.30	0.34	0.37	0.39	0.41	0.41	0.42	0.43
Annual mean potential evapotranspiration	-0.01	0.14	0.31	0.38	0.41	0.43	0.44	0.45	0.45	0.45	0.45
Aridity index	0.09	-0.18	-0.33	-0.39	-0.41	-0.43	-0.44	-0.45	-0.45	-0.45	-0.46
Elevation	0.11	0.12	0.17	0.23	0.27	0.29	0.31	0.33	0.34	0.35	0.36
Latitude	0.04	-0.02	-0.14	-0.19	-0.20	-0.21	-0.21	-0.21	-0.21	-0.21	-0.20
Clay content	-0.01	0.02	-0.03	-0.05	-0.07	-0.10	-0.12	-0.14	-0.15	-0.17	-0.19
Silt content	-0.03	-0.10	-0.16	-0.18	-0.19	-0.19	-0.19	-0.18	-0.18	-0.18	-0.18
Sand content	-0.09	-0.07	-0.04	-0.01	-0.01	0.00	0.01	0.02	0.03	0.04	0.05
Bulk density	-0.33	-0.39	-0.35	-0.32	-0.30	-0.29	-0.27	-0.27	-0.26	-0.25	-0.24
Soil organic carbon	0.06	-0.08	-0.18	-0.22	-0.24	-0.25	-0.25	-0.26	-0.26	-0.26	-0.26

Figure 6.12: Weighted Spearman rank correlation coefficients between K_h at different tensions and selected climatic features, the elevation above sea level as well as soil properties. The soil textures were classified using USDA texture classes as follows: fine (clay, clay loam, silty clay, silty clay loam), medium (silt loam, loam), coarse (loamy sand, sand, sandy clay, sandy clay loam, sandy loam).

ure 6.11). Strong correlations to at least one of these two variables with absolute values >0.6 were also found for most of the investigated climate variables. It is difficult to separate the climate effects due to these strong inter-correlations. But it stands out that not only the mean annual diurnal temperature ranges are much better correlated with K_{100} than the mean annual temperature itself. Also the mean annual precipitation in the driest quarter of the year and the precipitation seasonality index exhibited stronger correlations than the mean annual precipitation. It appears that temperature and precipitation fluctuations are more strongly coupled to near-saturated hydraulic conductivities than the absolute temperatures or precipitation amounts. In the following we attempt an explanation.

Larger diurnal temperature ranges may lead to larger near-saturated hydraulic conductivities because it might stimulate migration of soil macrofauna between topsoil and subsoil to prevent excessive heating or cooling. Burrow systems may therefore extend more in the vertical than the horizontal directions and reach further into the subsoil. Moreover, frequent large temperature shifts may be associated with larger changes in moisture conditions due to dew formation and subsequent evaporation. It also is connected with more frequent freezing thawing cycles. The correlation may also partly be driven by the moderating effect of large soil moisture contents on the diurnal temperature range. Soils with low K_h are expected to dry slower than soils with large K_h. Wet soils heat and cool more slowly than dry soils, because water has a large heat capacity and the phase changes occurring during evaporation or condensation add to decreasing the rate at which the soil heats up. Hence, small K_h buffer diurnal temperature shifts. It is not clear to what extent the observed correlation was driven by high diurnal temperature ranges causing high K_h or, the other way around, low K_h led to low diurnal temperature ranges.

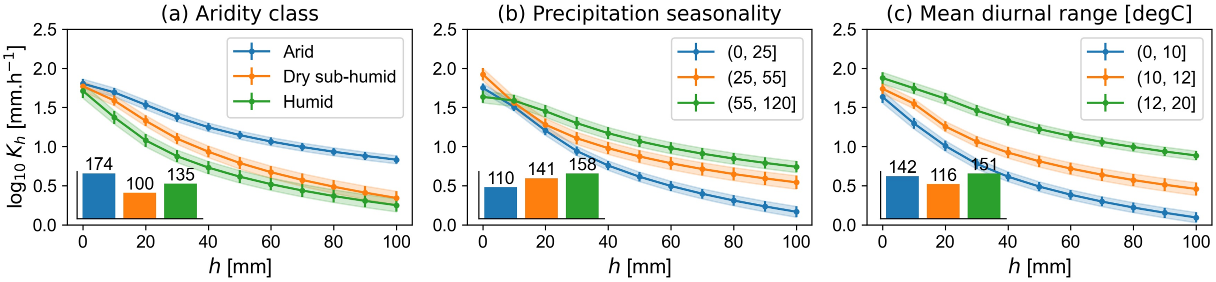


Figure 6.13: Weighted mean K_h as a function of applied tension for (a) aridity classes, (b) precipitation seasonality and (c) mean diurnal temperature range. The shaded areas and the error bars represent the weighted standard error of the mean.

The negative correlation between aridity index and K_h, i.e. the drier the climate, the larger K_h, is more intuitive. Dryness forces plants to grow deeper roots. It also forces the soil macrofauna to burrow deeper into the soil to prevent drying out. This creates vertical connected macropore systems which increase K_h. Large precipitation seasonality may contribute to larger K_h, because they indicate the presence of dry seasons, under which the topsoil dries out thoroughly, which may stabilise existing macrostructures in soil.

Another site factor that is positively correlated with K_h is the elevation above sea level (Figure 6.13). In the case of infiltrometer measurements, the decreased atmospheric pressure with height on the supply tension can be neglected. The supply tension is always equivalent to the weight of the water column adjusted for the measurement. The weight of the water column will be smaller due to the general decrease of earth's gravitational constant with height due to a larger centrifugal force. However, the weight of the water column would only be reduced by approximately one or two percent. Also, indirect influences of larger heights on the infiltration rate cannot explain the observed correlation. A lower temperature would make the water column heavier, however, the effect would be less than 1% in the relevant temperature range. In contrast, a lower temperature would increase the water's viscosity to a much larger degree, e.g. by up to approximately 30% between temperatures of 10 and 20 ^{o}C. The temperature effect should thus lead to a negative correlation between elevation and K_h, which is the opposite of what was observed. Physically explainable bias in the K_h measurements can thus be ruled out. The elevation may instead be a proxy for well-drained soils, as stagnant soil water and high groundwater tables are less likely with height above sea level. This may favour soil life and better developed root systems. Notably, the elevation above sea level also was found to be an important predictor for K_s in Gupta et al. (2021b), which suggests that there are indeed pedogenetic reasons behind the observed correlation.

Bulk density was the only soil property that exhibited (negative) correlation strength of >0.3 to any K_h (Figure 6.13). The underlying reasons have been discussed above. Notably, the strongest correlations were found at and very close to saturation due the direct link between bulk density and macroporosity. The more compaction, the less macroporosity remains and the higher the bulk density. In addition, this then again negatively impacts the options for root growth and bioturbation.

Effects of land use, tillage, compaction and sampling time

Figure 6.14 shows the average $\log_{10}$ response ratio of K_h for $0 \quad h \quad 100$ mm for different land uses and soil management options. Arable land exhibited clearly smaller K_s than grasslands and forests, which is in line with observations made by Basche and DeLonge (2019). This difference became smaller with higher tensions (Figure 6.14a). The large difference in K_h close to saturation was likely related to traffic compaction as well as tillage operations that were applied to the majority of the investigated arable soils, which lead to the destruction of connected biopores and hence a reduced K_s. On the other hand, tillage breaks up intact soil into individual soil aggregates, which creates, at least initially, a well-connected network of inter-aggregate pores that increase K_h in the near-saturated range (Sandin et al., 2017; Schlüter et al., 2020). This effect of tillage can explain why near-saturated K_h under conventional and reduced tillage was larger than under no-till (Figure 6.14b). However, in this case, even K_s was larger in the tilled fields. It is likely that K_s was reduced in the no-till treatments due to more trafficking on the fields as compared to non-arable treatments. The impact of soil compaction on K_h was clearly negative in the entire investigated range of tensions (Figure 6.14c), which is explained by the reduction of porosity, and especially the macroporosity during compaction (see also Figure 6.10b). In contrast, if the K_h measurements were carried out shortly after tillage operations, K_h was increased for all investigated tensions, especially very close to saturation (Figure 6.14d). This confirms that tillage initially increases K_s, but that subsequent soil consolidation preferentially disconnects the largest macropores. As a consequence, K_h at and very close to saturation is reduced more strongly than K_h for higher tensions.

Figure 6.15 shows the results of the sensitivity analyses for the effect sizes depicted in Figure 6.14. The effect of land use for K_{100} turned out to be the most sensitive to removals of studies (Figure 6.15a). The direction of the effect even changed after removal of only two studies, indicating that higher K_{100} for arable compared to non-arable fields were not just occasional observations but occurred more frequently. More studies would be needed to properly characterise the effect of land use on K_{100}. The sensitivity analyses for all other factors for both, K_{100} and K_s all yielded that removal of studies did not change or destabilise the results. The large majority of the respective studies in OTIM-DB had observed similar effects, thus validating them.

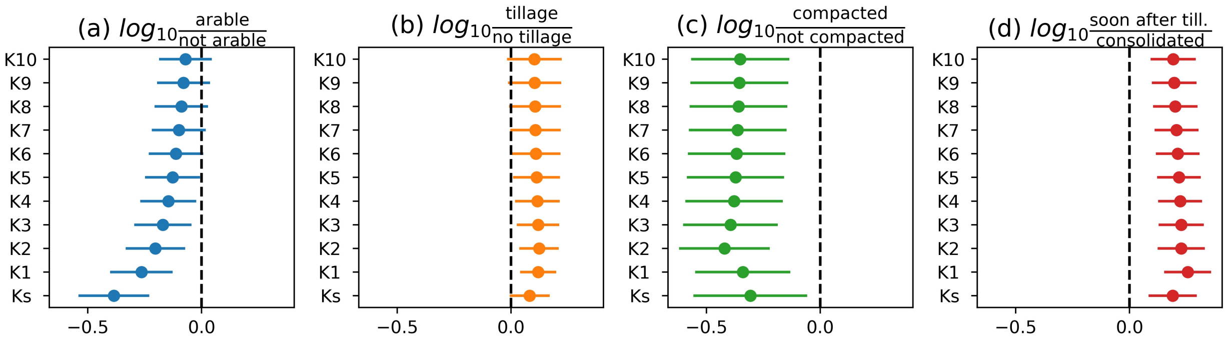


Figure 6.14: Weighted mean $\log_{10}$ response ratio (effect size) of K_h for from K_{100} to K_s for different management practises where the controls were 'not arable', 'no tillage', 'no compaction' and 'consolidated soil' respectively. Positive effect size means that the value of the treatment is greater than the control. Dashed line shows the "no effect" (no difference between treatment and control). Error bars represent the weighted standard error of the mean.

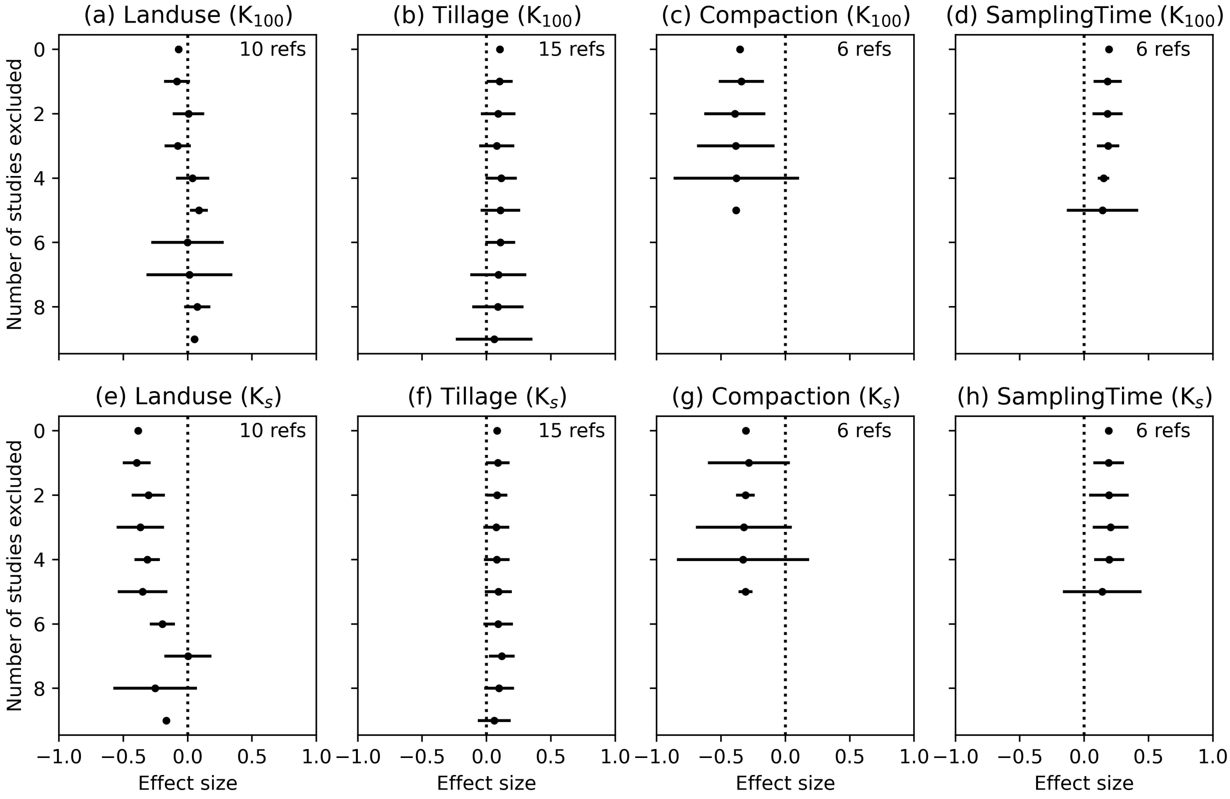


Figure 6.15: Sensitivity analysis of the weighted effect size of K at 100 mm tension and K_s for the management practice investigated using the Jackknife technique. The error bars represent the standard error.

Publication bias

The histograms of the effect sizes for K_{100} are shown in Figure 6.16. For the tillage factor we observed a slight bias towards positive effect sizes, which may indicate publication bias, with more likely publications in case that conventional or reduced tillage yielded larger K_h than no-till. The small number of studies available in OTIM-DB to compute the effect sizes for compaction and sampling time makes it hard to obtain a smooth shape for the distribution and limits our ability to estimate bias for compaction and sampling time.

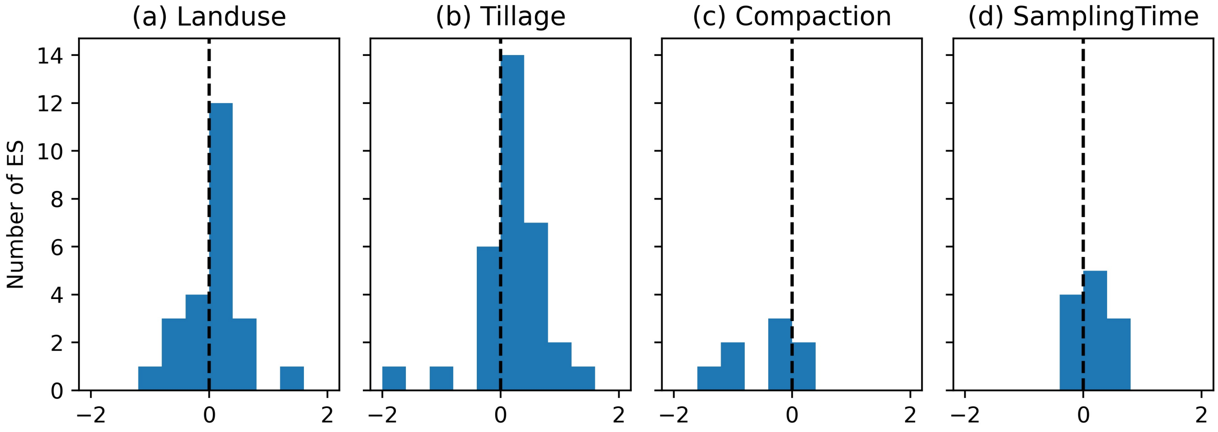


Figure 6.16: Histogram of effect sizes for each factor.

6.4.3 Conclusions of meta-analyses part

We observed the strongest correlations between climate variables and K_h, namely diurnal temperature range, aridity and precipitation seasonality. In the dryer range of investigated supply tensions, these correlations were clearly larger than correlation between K_h and soil properties like texture and organic carbon content. Our results suggest that climate change will influence soil hydraulic properties at and near saturation, complicating estimations for future risks of surface runoff with soil erosion and water-logging. On the one hand, this confirms the findings of Jarvis et al. (2013), Jorda et al. (2015) and Hirmas et al. (2018) that climate variables influence saturated and near-saturated soil hydraulic conductivity. On the other hand, the large positive correlation between K_{100} and the mean annual temperature reported in Jarvis et al. (2013) on a part of the here investigated dataset was not found back. The importance of the above mentioned climate variables for K_h should be confirmed by additional measurement. Hypotheses of how these climate aspects influence K_h mechanically were presented in the results and discussion parts but need to be further investigated, as should be the large correlation of elevation above sea level to K_h.

At and very close to soil saturation, the correlation between K_h and the climate variables vanished. Instead, the soil bulk density showed the largest correlations. For this saturation range, land use and land management seemed to be more important, as tillage and soil compaction due to trafficking are known to lead to larger bulk densities. In this context we found that it is very important to take the time period after the last tillage into account, after which the tension-disk measurement was conducted, as larger K_h were measured shortly after tillage. Last but not least, our meta-analyses demonstrated that there is a need for better documentation and availability of measurement and associated meta-data. In our case, the lack of reporting standard deviations of the K_h measurements in log-space prevented a thorough analysis of potential publication bias. Missing information of land use and soil management and cropping practises and their history made it challenging to quantify their impacts on K_h. We therefore want to stress the need for better experimental documentations and open access to research data, as it has already demanded before (McBratney et al., 2011; Basche and DeLonge, 2019).

6.5 Machine learning

6.5.1 Material and methods

Machine learning approach: Light Gradient Boosting regression model

We used a tree-based model, namely the Light Gradient Boosting (LGB) regression model (Ke et al., 2017), because this group of machine learning approaches allows for an easier interpretation of effects and importance of individual predictors. Tree-based machine learning models combine the predictions of decision trees using different styles of ensemble techniques. The term 'boosting' denotes a type of model that improves its predictions by giving samples with a large prediction error more weight in the fitting process with each training iteration. Usually, boosting methods outperform other tree methods. LGB is known to perform overall well for different machine learning tasks. The LGB model also performed best in preliminary trial runs on the OTIM-DB data. We used the *lightgbm* Python package (v3.2.1) to apply the LGB model to our data.

Data pre-selection and data weighting

As discussed, tree-based models are able to handle missing data. Nevertheless, too much missing information decreases the predictive performance of these models. For this reason, only predictors that contained at least 50% of the maximally possible number of data entries were considered for the modelling procedure.

We used the same weighting scheme as in the meta-analyses (see Equation 6.1) to avoid bias due to different amounts of entries over source publication and different number of replicates from which individual data entries were averaged.

Feature engineering

While tree-based methods are able to use categorical data without any transformation, we decided to encode all categorical values into numerical ones as then more information is provided for the model. For instance, tillage type was classified into three classes in OTIM-DB: conventional tillage, reduced tillage, and no-tillage. Assigning them values of 2, 1 and 0, respectively, allows classification on tillage intensity and not just on different tillage types. The conversion of the majority of categorical variables into numeric ones was carried out using Catboost encoding Prokhorenkova et al. (2018), which is a type of target encoding. Target encoding assigns the average value of the target variable for specific entries of a categorical variable. For example, it replaces the categorical value 'conventional tillage' with the average K_s of all measurements on conventionally tilled sites in the database. A drawback of simple target encoding is that only three different values would become possible in the example of the tillage predictor as available in OTIM-DB. This does not favour selection of this variable in the LGB model. Catboost encoding uses averages of randomised subsets of all respective target values instead. As a result, a categorical variable with only two or three possible values is encoded into a continuous numeric variable with as many possible different values as there are unique data entries in the database.

We encoded the predictors 'crop rotation' and 'season' a different way. Crop rotations stored in OTIM-DB are very diverse. Almost each source publication reported a unique crop-rotation scheme. The individual crop-rotation schemes would therefore act as an identifier for a respective source publication. Therefore, it must not be encoded in with a simple Catboost approach. Another problem arises because for such a simple encoding, similar rotations e.g., maize-maize-wheat and maize-wheat would be classified as being completely different. Instead, we used a semi-one-hot encoding approach. In the original one-hot encoding, a new binary predictor is introduced for each unique entry of a categorical variable, which is one if the unique entry is true or zero if it is false. For semi-one-hot encoding, we classified the crops according to plant classes, e.g. cereals, fruit trees or grasses. Each of these subclasses held entries associated with this class like wheat, barley or oats for cereals. A new binary predictor for each subclass was created. It was filled with a one if one of the entries was contained in the underlying crop rotations and a zero otherwise. This procedure did not increase dimensionality drastically and introduced similarity within similar rotations. Afterwards, we encoded these new crop-class predictors using Catboost encoding to make them more suitable for the LGB model algorithm.

The cyclic predictor 'season' was encoded into two predictor

$$S_{sin} = \sin\frac{2\pi x}{x_{tot}} \text{ and } S_{cos} = \cos\frac{2\pi x}{x_{tot}} \tag{6.5}$$

where S abbreviates the 'season' predictor, x (-) is the season with values of 0, 1, 2 and 3 for spring, summer, autumn and winter, respectively and x_{tot} (-) is the number of seasons in a year, i.e. 4. This cyclic encoding conveys the information to the machine learning algorithm that spring is following winter.

Data imputation

Albeit that LGB can handle missing values, we filled data gaps using a random forest trained on the available data (*Python* package *MissForest*, Sekhoven & Bühlmann, 2011). This allowed us to use an advanced feature selection approach in the LGB hyper-parameter optimization (see below).

LGB training and validation

We used two different cross-validation schemes to train and validate the LGB model.

i) Naïve cross-validation

Naïve cross-validation denotes simple 10-fold cross-validation Hastie et al. (2009). All available data entries were randomly assigned to ten different groups. We referred to the groups as folds in the following. We trained the LGB model on the data from nine of the folds and subsequently validated the trained model using the data of the remaining tenth group. Then, another fold was selected for validation and another LGB model was trained on the data from the respective remaining nine folds. This was done ten times in total, so that ten different LGB models were trained and a prediction was available for each data entry. The validation results of the naïve cross-validation reflect the predictive performance of the LGB model under the assumption that the dataset used to train it was a representative sample of the total statistical population. Considering the biassed and sparse distribution of sampling sites around the globe as well as the plethora of different possible influencing factors and the amount of gaps in the data collected in OTIM-DB, this assumption was most likely not met in our study. Therefore, it was expected that naïve cross-validation would result in over-optimistic validation results.

ii) Source-wise cross-validation

The source-wise cross-validation was already used in Jorda et al. (2015). It is also a 10-fold cross-validation. However, this time, data entries of individual source publications were all contained in only one of the ten folds, respectively. The fold used for the model validation hence only included data-entries from studies that were unknown to the trained LGB model. Source-wise cross-validation hence simulates prediction of data from a new source. Its results are therefore realistic for applications of a final LGB model as a pedotransfer function. The source-wise cross-validation also resulted in ten LGB models and model predictions for each data entry.

Quantifying predictor importance

We used the SHAP (SHapley Additive exPlanations) importance to evaluate the importance of individual predictors on the model prediction Lundberg and Lee (2017). The SHAP importance is calculated by checking the difference of the model performance with and without a certain feature taken into account. Features that show a large predictive improvement when selected achieve a higher importance. SHAP values of a predictor quantify how much this predictor contributes to a prediction given a base value. The base value refers to the predicted target variable of the model without the predictor. For example, a predictor with a SHAP value of 0.2 mm.h^{-1} changes a prediction of the hydraulic conductivity from 1 mm.h^{-1} (base value) to 1.2 mm.h^{-1} (model prediction with the predictor). SHAP values increase the interpretability of predictor importance, since they provide a measure that quantifies the direction and the magnitude of the influence of the predictor on the target variable, expressed in the same units.

In the following, we investigated SHAP values based on the validation data of the source-wise cross-validation scheme. The SHAP value reflects the predictor importance to re-estimate the hydraulic conductivities presently stored in OTIM-DB. It must not be forgotten that the here discussed SHAP importance for predicting K_h has to be seen relative to the data in OTIM-DB from which it was derived. Only if the OTIM-DB data can be viewed as representative for K_h measurements in general, the SHAP importance is also generally valid. Otherwise, it will partly reflect biases in the OTIM-DB data.

When interpreting predictor importance of a machine learning approach, it also must be kept in mind that it depends not only on the data that was used to train the model, but also on the hyperparameterization and the selected predictors (see next section). Quantifying these dependencies turned out to be too time consuming to be carried out within the framework of our study.

LGB model optimization including feature selection

Model optimization is a part of model training and is included in any machine learning workflow. It aims to enhance the results of a model and reduce computation time when making predictions. In our study, we carried out hyper-parameter optimization and feature selection. Hyper-parameters are parameters that govern the model building process. They need to be adjusted to minimise both, under and over-fitting. Common hyper-parameters of tree-based models are the number of branches used per individual decision tree or the total number of trees used. For example, trees with many branches are prone to overfitting. Trees with insufficient branches may not be able to represent the complexity of the fitted data, which would lead to under-fitting.

Feature selection describes an approach in which a subset of useful predictors is chosen from all available predictors to exclusively train the model. Usually feature selection increases the model performance slightly or at least does not worsen the prediction results, while it strongly reduces the required computational power. We applied the Boruta method described in Kursa and Rudnicki (2010), using the *Python* package *BorutaSHAP*. The method works by creating a so-called shadow predictor for each original predictor, which contains a random permutation of the values of the original predictor. The expected correlation of each shadow predictor with the target variable is therefore zero. We then trained an LGB model with both, original and shadow predictors. Each predictor whose SHAP importance for the model was smaller than the SHAP importance of the most important shadow predictor was deselected. Since this procedure depends heavily on the realisation of the random permutation of the original predictor values, the Boruta approach was performed 20 times using different random seeds. Only predictors were selected that were more important than the best shadow feature.

Because hyper-parameters influence feature selection and vice versa, we used an iterative approach to implement both. Here, a first optimization of the most basic hyper-parameters was performed using all predictors. We used the *Python* package *Optuna* (Akiba et al., 2019) to carry out the hyper-parameter optimization. *Optuna* uses a tree-structured Parzen estimator for predefined discretized values within predefined boundaries for individual hyper-parameters. The model hyper-parameters were optimised to reduce the root mean squared error (RMSE) of either the naïve or the source-wise cross-validation scheme. From trial and errors, some hyper-parameters were found to not have a great influence on the final results and hence, were left out of the hyper-parameters optimization scheme. Other hyper-parameters were pre-set to values that led to good prediction performances when they were optimised in preliminary trial runs for the source-wise cross-validation scheme. The pre-set and optimised hyper-parameters and their discretization and optimization boundaries are listed in Table 6.4. After the most suited features were selected using the Boruta method, we again optimised the selected hyper-parameters using the specifications collected in Table 6.4. 50 iterations for each optimization were found to be sufficient to yield stable results.

Nesting of model training, validation and testing

The training aims at fitting the parameters of the models. The validation is used to optimise the hyper-parameters. The testing aims at estimating the performance of the fitted model on an unseen dataset. We used a fully nested approach for model training, validation and testing. In an outer loop, we trained and validated the LGB model on the data in nine of ten folds. The trained model was then tested against the remaining fold. Model training and validation were carried out using an inner ten-fold cross-validation loop. The nine folds from the outer loop were split up into ten inner folds, of which nine were used for model training (including feature selection) and the remaining fold was used for model validation. Either the naïve or the source-wise cross-validation schemes were used for both, inner and outer cross-validation loops, respectively.

While training, validating and testing models using the source-wise cross-validation scheme, we noticed the results of the model testing depended strongly on how the data from individual source publications were distributed on the randomly created folds. No such problems were observed for the naïve cross-validation scheme. In order to yield representative results for the source-wise cross-validation, we repeated the model training, validating and testing 10 times, each time with a different realisation of the ten folds. For each of the ten realisations, we calculated a coefficient of determination R^2 using

$$R^2 = \frac{SR_{CV}}{SS_{tot}} \tag{6.6}$$

where SR_{CV} is the sum of squared residuals assembled from the ten model test results in the outer cross-validation loop and SS_{tot} is the total sum of squares, using all available data.

Table 6.4: LGB hyper-parameters with boundaries and discretization within which they were optimised or pre-set values that had been determined in preliminary optimization runs. All LGB parameters not listed here were set to their default values in the *LightGBM Python* package. The optimised median hyper-parameter values were obtained from the 1010 realisations for optimised values that were available from the inner cross-validation loops for all considered hydraulic conductivities. The values were taken from the respective optimization rounds after the Boruta feature selection. The label 'log-scale' indicates that there was no discretization applied but that the parameter search was conducted in log-space.

hyper-parameter	**boundaries (discretization)**	**pre-set or median optimised value**
n_estimators	-	2000
num_leaves	3 .. 51 (3)	27
learning_rate	-	0.075
max_depth	-	4
num_iterations	-	200
max_bin	-	16
min_child_samples	30 .. 70 (5)	50
reg_alpha	-	0.001
reg_lambda	-	0.001
min_split_gain	0.01 .. 3 (log-scale)	0.051

6.5.2 Results and discussion

Prediction Performance

When implementing the naïve cross-validation scheme, the median prediction performance yielded coefficients of determinations R^2 varying between 0.62 and 0.73, depending on the supply tension for the predicted hydraulic conductivity K_h (Figure 6.17). For the source-wise cross-validation scheme, the R^2 dropped below zero for K_h at and near saturation and only reached small positive values at supply tensions of 30 mm or more. It follows that the LGB model is not able to predict K_h for datasets presently not included into OTIM-DB with satisfying precision. The good results for the naïve cross-validation show however that decent predictions were obtained if data entries from the respective source publication are leaked into the training set. This may be taken advantage of by using an approach referred to as "spiking" in the literature (Viscarra Rossel et al., 2009), i.e. by including K_h measurements for a new measurement site into the LGB model training set. A thus trained model may then be suitable to predict K_h at all locations within the new site for which respective meta-data is available.

The large difference in prediction performance between results from naïve and source-wise cross-validation schemes may have one or a combination of several reasons. It may be that the OTIM-DB data is afflicted with a large experimenter bias, probably associated with differing approaches to establish contact between the tension disk and the soil surface. Then, the OTIM-DB dataset may simply not be representative for the diversity of influencing factors existing for K_h at a global level. Another obvious explanation is that the proxy variables available in OTIM-DB were simply not very well suited to predict K_h.

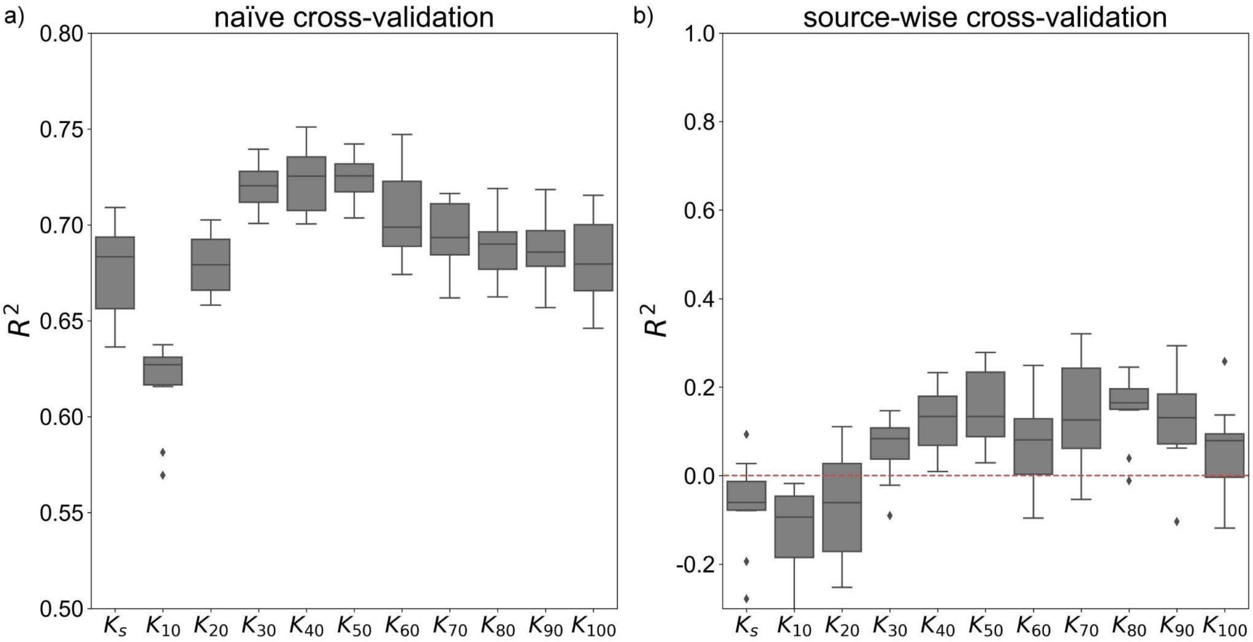


Figure 6.17: LGB model prediction performance for (a) the naïve and (b) the source-wise cross-validation schemes of the ten realisations of the nested training, testing and validation loop for each investigated supply tension, respectively. Note that the scales for the y-axes differ between (a) and (b).

Important predictors

Figure 6.18 illustrates Boruta feature selection frequencies as a measure for predictor importance for K_s and K_{100}. Note that a lack of correlation between predictor and its SHAP value like for the soil organic carbon content in Figure 6.18b does not necessarily imply that the relationship was fundamentally shifting for each realisation of the ten-fold cross-validations. It may also mean that the relationship was stable but non-linear. Remember that correlations for categorical variables like the WRB soil type were related to Catboost-encoded values. They can only be properly interpreted with taking the encoding into account. The relationship between decoded WRB soil types and their SHAP and K_{100} values are shown in Figure 6.19.

The importance of individual predictors changed for K_h with supply tension, but converged to a stable set of predictors for drier conditions (Figure 6.20). The most important predictors for K_s (Figure 6.20a) were the longitude of the measurement location and cereals within the crop rotation implemented at the measurement site. For both we found it is difficult to explain why they should have a stronger impact on K_s than e.g. the bulk density. It is possible that the longitude encodes experimenter bias between researchers in the USA and Europe, the two global regions from where the majority of OTIM-DB data-entries stem. Alternatively, it may encode the more continental climate of North America as compared to Europe, under which then soils with different K_h had developed. Similar speculations may be undertaken to explain the impact of cereals in the crop rotation. However, we suspect that most of the predictors with large Boruta selection frequencies for estimating K_s rather expressed random bias in the OTIM-DB dataset, i.e. the seemingly high importance of these predictors was associated with artefacts from over-fitting. This view is supported by the fact that the LGB model was not able to predict K_s with R^2 of more than zero.

The bulk density, in contrast, was likely a predictor that was assigned large importance due to its causal relationship with K_h. It showed up prominently among the most important predictors for supply tensions smaller than 50 mm (Figures 19a and 21). A large bulk density was always associated with a decrease in K_h. This reflects empirical knowledge. The correlation analyses in section XY likewise indicated the largest impact of bulk density on K_h near saturation. We therefore infer that the bulk density is a predictor whose usefulness for estimating K_h at and near-saturation is beyond doubt.

Notably, land use, tillage type, compaction or time of measurement only occasionally entered the lower ranks of the ten most frequently selected predictors, albeit they were shown to coincide with clear alterations in K_h in the meta-analyses (Section 6.4.2). Apparently, their impact was strongly dependent on the context, e.g. when comparing tilled with no-till arable fields. It may be that the rather simplistic design of our predictor importance analysis could not extract this context specific information. Using a simpler machine learning approach like a random forest may have had advantages in this respect, as Koestel and Jorda (2014), when using a random forest to predict the strength of preferential flow, were able to identify predictors that became only important under specific circumstances.

At the dry end of the considered supply tension range, the mean diurnal temperature range, the method to convert infiltration rate to K_h, the WRB soil type and the USDA soil texture were the most important predictors (Figure 6.18b and Figure 6.20). The first two already had been discussed in the meta-analyses (Section 6.4.2). The mean diurnal temperature range showed the largest correlation with K_h for supply tensions larger than 10 mm. It is unclear what the reason for the large correlation is. Among the methods to convert infiltration rate to K_h, it is especially the ‘steady-state constant’ method that is known to overestimate K_h in the dry end of the here investigated tension range. As discussed, the impact of WRB soil type can only be understood with the aid of its relationship to K_h.

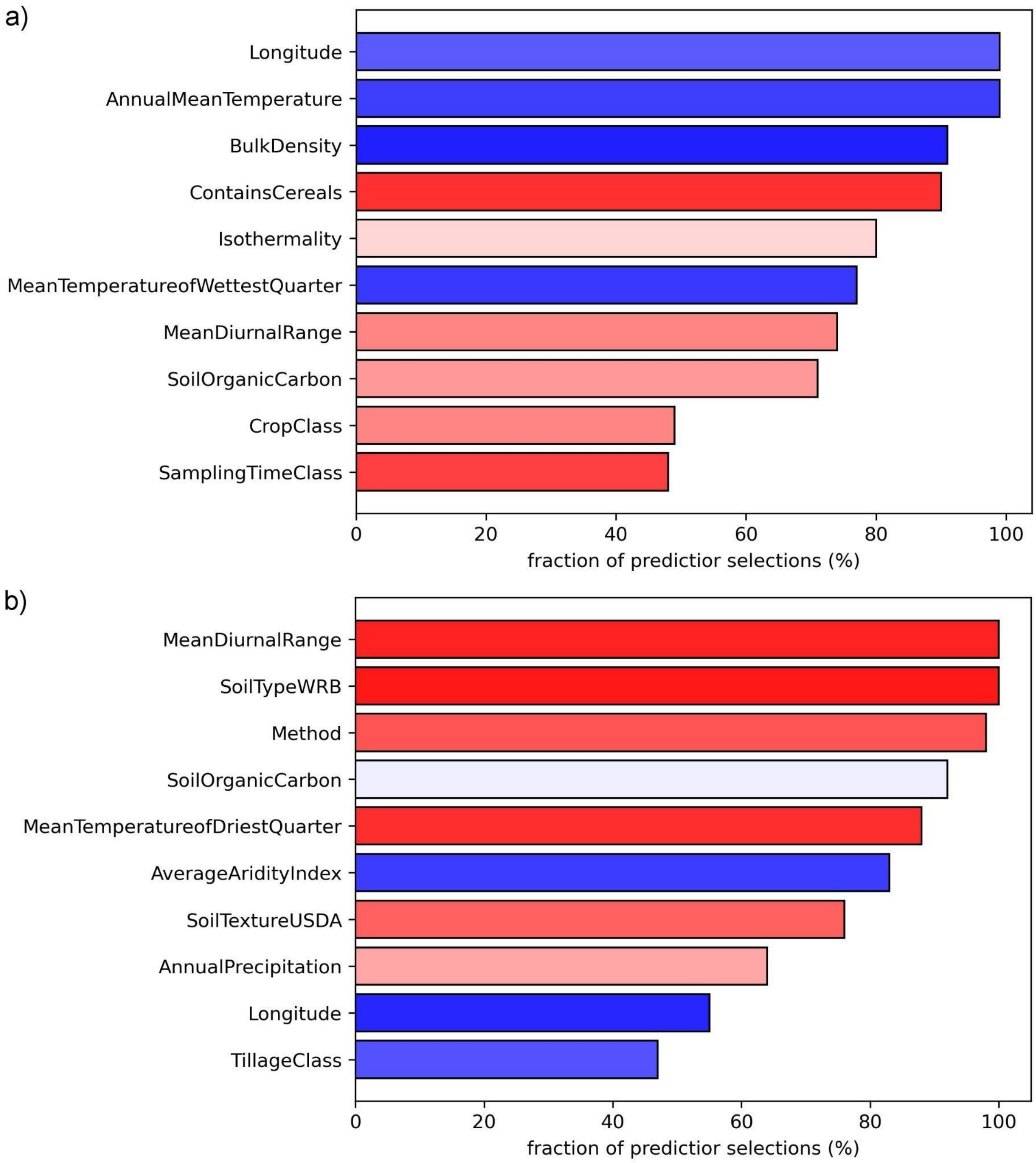


Figure 6.18: The ten most important predictors for (a) K_s, and (d) K_{100} resulting from the naïve cross-validation scheme. Red, white and blue colours indicate positive, absent and negative Pearson correlations of the predictors' SHAP values with the respective K_h. The selection frequency refers to the Boruta feature selection.

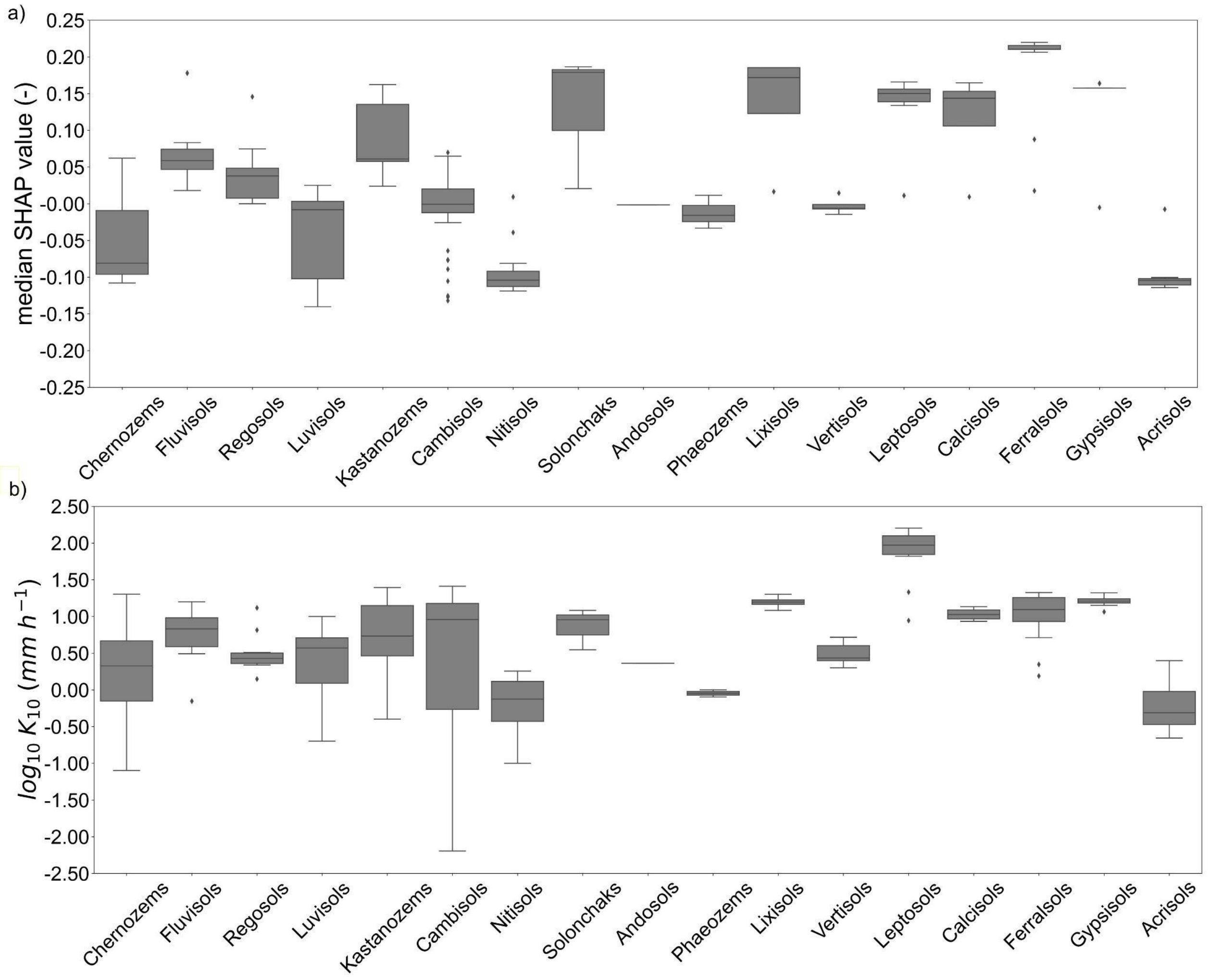


Figure 6.19: (a) SHAP values of individual WRB soil types and (b) the respective K_{100}. Positive SHAP values means the predictor contributes positively to the prediction of K.

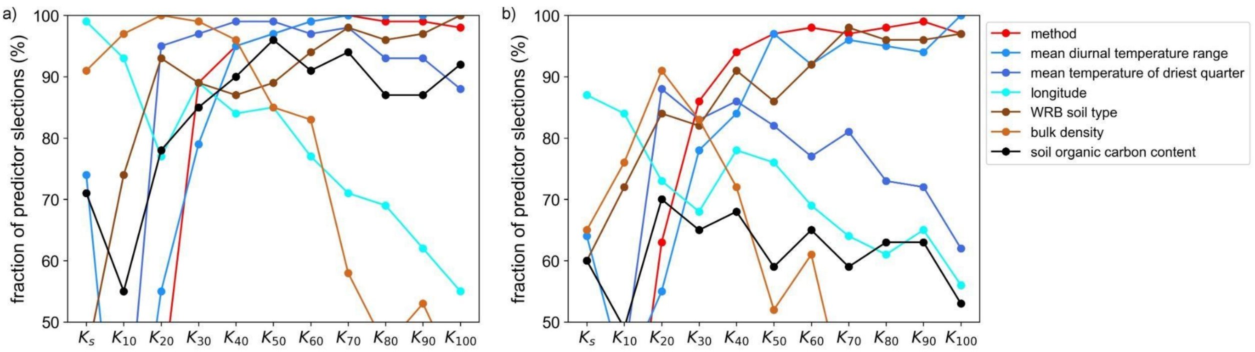


Figure 6.20: Selection frequency of some individual predictors in the Boruta feature selection for (a) the naïve cross-validation and (b) the source-wise cross-validation schemes.

Figure 6.19 illustrates that the respective SHAP values follow the K_{100} observed for individual soil types. This is in line with the positive correlation between WRB soil type SHAP values and K_{100} indicated in Figure 19b. It may be doubted if the association of K_{100} with specific soil types in OTIM-DB was representative for the general case. The large K_{100} for Leptosols may result from the fact that these soils often develop on coarse gravel. Also the low K_{100} for Acrisols are consistent with the low structural stability of this soil type. However, Nitisols are generally associated with large hydraulic conductivities, while the opposite was observed for the Nitisols in OTIM-DB. Whether WRB soil types are truly useful predictors for the near-saturated hydraulic conductivity needs to be investigated on a larger set of data.

Eventually, we want to mention that the soil organic carbon content was constantly among the ten most important predictors (see Figure 6.20). However, it always remained in the lower half of these lists. This may indicate that the soil organic carbon content is a predictor that is useful to further classify K_h after its value was already roughly estimated by more important predictors. Notably, the soil organic carbon content was positively correlated with K_s and negatively with K_{100}, mirroring the correlations observed in the meta-analyses (see Section 6.4.2 and discussions therein).

6.5.3 Conclusions of machine learning part

The LGB model trained in our study is not suited to serve as a pedotransfer function for the saturated and near-saturated hydraulic conductivity, because its prediction performance is clearly too low. The failure of developing a functioning pedotransfer function was most probably associated with i) a lack in suitability of the available proxy variables as predictors, ii) an insufficient amount of data points to estimate K_h using weak predictors and iii) experimenters' bias. The Python code published in form of a Jupyter notebook alongside with this report may however be used to train LGB models tailored to new measurement sites if the models are spiked with a number measurements and meta-data from this new site.

The importance of predictors for K_h at and very close to saturation are probably not trustworthy, with exception of the bulk density. The most important predictors for K_h at the dry end of the investigated tension range are consistent with correlations observed in the meta-analyses and are predominantly backed by empirical knowledge. Our results support the conclusion of the meta-analyses part of our study that there is a need to investigate the reasons for the large observed correlations of climate variables like the mean diurnal temperature range or the mean temperature of the wettest quarter of the year with K_h. Context-specific relationships could barely be extracted using the LGB model predictor importance. At least, the absence of land use and soil management practises among the most important predictors indicate that, while they were shown in the meta-analyses to affect K_h, their impact is constraint to specific contexts, e.g. it is only observable when arable fields are considered.

6.6 General conclusions

We confirmed significant correlations between climate variables as well as the elevation above sea level with saturated and near saturated hydraulic conductivity. While it seems very likely that these variables influence soil physical properties, the exact underlying mechanisms need to be investigated in future studies. We found indications that specific soil management practises lead to changes in saturated and near-saturated hydraulic conductivities, which were increased under perennial cultures and decreased for no-till arable fields with annual crops and for compacted soil. Our data also confirmed that it is fundamental to take the time of the measurement after the last tillage operation into account to understand relationships between soil management and saturated and near-saturated hydraulic conductivity. Note that the management impacts turned out to be dependent on the pedo-climatic context, as they only could be observed if variations in the latter were ruled out. We also found that the data availability for tension-disk infiltrometer data was too scarce and riddled with too many gaps for detailed analyses of other soil management impacts, more specific pedo-climatic context dependencies and publication bias. Furthermore, we found indications that the available data was afflicted with experimenter bias. Altogether, it was not possible to predict saturated and near-saturated hydraulic conductivities from the available data for new sites, which echoes results of similar attempts to build respective pedotransfer functions. More measurements with better documented meta-data and better suited predictor variables would be needed for progress in this field. Studies quantifying soil structure evolution with respect to season, land use and soil management using X-ray imaging may turn out to provide useful information for more appropriate proxy variables for the saturated and near-saturated hydraulic conductivities.

Chapter 7

Natural language processing as a tool to explore the information in vast bodies of literature

Summary

Climate change will most likely lead to an increase of extreme weather events, including heavy rainfall with soil surface runoff and erosion. Adapting agricultural management practices that lead to increased infiltration capacities of soil has potential to mitigate these risks. However, effects of agricultural management practices (tillage, cover crops, amendment, . . .) on soil variables (hydraulic conductivity, aggregate stability, . . .) often depend on the pedo-climatic context. Hence, in order to be able to advise stakeholders on suitable management practices, it is important to quantify such dependencies using meta-analyses of studies investigating this topic. As a first step, structured information from scientific publications needs to be extracted to build a meta-database, which then can be analyzed and recommendations can be given in dependence to the pedo-climatic context.

Manually building such a database by going through all publications is very time-consuming. Given the increasing amount of literature, this task is likely to require more and more effort in the future. Natural language processing (NLP) facilitates this task. In this work, two sets of documents (corpus) were used: the OTIM corpus contains the source publications of the entries of the OTIM-DB of near-saturated hydraulic conductivity from tension-disk infiltrometer measurements and the Meta corpus is constituted of all primary studies from 36 selected meta-analyses on the impact of agricultural practices on sustainable water management in Europe. We focused on three NLP techniques: i) we used of topic modelling to sort the individual source-publications of the Meta corpus into 6 topics (e.g. related to cover crops, biochar, . . .) with an average coherence metric Cv of 0.68; ii) we used tailored regular expressions and dictionaries to extract coordinates, soil texture, soil type, rainfall, disk diameter and tensions on the OTIM corpus. We found that the respective information could be retrieved relatively well, with 56% up to 100% relevant information retrieved with a precision between 83% and 100%; and iii) we extracted relationships between a set of “driver” keywords (e.g. ‘biochar’, ‘zero tillage’, . . .) and “variables”, i.e. soil and site properties (e.g. ‘soil aggregate’, ‘hydraulic conductivity’, ‘crop yield’,. . .) from the source-publications’ abstracts of the Meta corpus using the shortest dependency path between them. These relationships were further classified according to positive, negative or absent correlations between the driver and soil property. This latter technique quickly provided an overview of the different driver-variable relationships and their abundance for an entire body of literature. For instance, we were able to retrieve the positive correlation between biochar and crop yield as well as the negative correlation between biochar and bulk density, both of which had been independently found to be present in the investigated meta-database.

Overall, the three NLP techniques from the simplest regular expression to the more complex re-

lationships extraction were able to support evidence synthesis tasks such as selecting relevant publications on a topic, extracting specific information to build databases for meta-analysis and providing an overview of relationships found in the corpus. While human supervision remains essential, NLP methods have the potential to support fully automated evidence synthesis that can be continuously updated as new publications become available.

7.1 Introduction

The effect of agricultural practices on agroecosystems is highly dependent upon other environmental factors such as climate and soil. In this context, summarizing information from scientific literature while extracting relevant environmental variables is important to establish pedo-climatic specific conclusions. This synthesis is essential to provide recommendations for soil management adaptations that are adequate for local conditions, both, today and in the future. Efforts to synthesize context-specific evidence through meta-analysis or reviews requires a lot of manual work to read respective papers and extract relevant information. This effort scales with the number of available relevant publications. In the meantime, the use of automated methods to analyze unstructured information (like text in a scientific publication) has been developing during recent years and has demonstrated potential to support evidence synthesis (Haddaway et al., 2020). Natural language processing (NLP) is one of them. In their review on the advances of the technique, Hirschberg and Manning (2019) explained that "Natural language processing employs computational techniques for the purpose of learning, understanding, and producing human language content." This definition is quite broad as NLP encompasses several considerably different techniques, like machine translation, information extraction or natural language understanding. Nadkarni et al. (2011) and Hirschberg and Manning (2019) provide a good overview on this field of research and how it originally developed. For applications to scientific publications, Nasar et al. (2018) reviewed different NLP techniques (information extraction, recommender systems, classification and clustering and summarizations). However, one limitation of supervised NLP techniques is that they require labels that need to be manually produced to train the model. Hence, humans are still needed for evidence synthesis but can certainly receive great support from existing NLP techniques.

NLP methods are most widely used in medical research. The development of electronic health records significantly facilitated the application of automatic methods to extract information in this field of research. For instance, information extraction techniques were used to identify adverse reactions to drugs, identify patients with certain illnesses which were not discovered yet at the time or link genes with their respective expression (Wang et al., 2018). A specific example is given by Tao et al. (2017) who used word embedding and controlled random fields to extract prescriptions from discharge summaries. Wang et al. (2018) provide an extensive review of the use of NLP for the medical context.

The rise of open-source software tools such as NLTK (Loper and Bird, 2002) and SpaCy (Honnibal and Montani, 2017) together with the increase in digitally available information has fostered the way for NLP applications to other scientific communities. For example, SpaCy is able to automatically separate the words of a sentence (word segmentation) but also recognize their nature and dependence on other words using a combination of rules-based and statistical methods. In the context of information extraction too, open-source tools exist also in the context of information extraction. A very popular tool is the OpenIE framework of the Stanford group (Angeli et al., 2015) included in the Stanford coreNLP package (Manning et al., 2014). Niklaus et al. (2018) present a review of open information extraction codes. All these tools greatly reduce the knowledge required to start using NLP technique and therefore supports NLP applications.

In the context of evidence synthesis, several NLP methods can be useful. Topic modeling can help group publications which are on the same topic but also assign a new publication to a given topic. In addition to selecting publications to be reviewed in the evidence synthesis , this also gives an overview of the number of publications per topic and potentially can help to identify knowledge gaps. Regular expressions search the text for a pattern of predefined numbers and words. They have a high precision but only find what they are designed to find. They can be augmented by including syntaxic information such as the nature (noun, adjective, adverb, . . .) and function (verb, subject, . . .) of a word. Complemented with dictionaries that contain lists of specific words (e.g. WRB soil groups), it can be a powerful method. More advanced NLP techniques aim at transforming words into numerical representations that can be further processed by numerical machine learning algorithms. For instance, word embedding are vectors which encode information about a word and its linguistic relationships in the context it is found. They are derived from the corpus of documents available. Another advanced technique for doing such conversion include transformer networks such as BERT which is a deep learning neural network that converts text to a numerical representation (Koroteev, 2021). BERT transformers are trained on specific corpus. For instance bioBERT is tailored to the medical context (Lee et al., 2020).

In contrast to the medical context, fewer studies applied NLP methods to soil sciences. Padarian et al. (2020) used topic modeling in their review of the use of machine learning in soil sciences. Furey et al. (2019) presented NLP methods to extract pedological information from soil survey description. Padarian and Fuentes (2019) used word embedding. Using the multi-dimensional vectors (=embedding), they were able to establish relationships between soil type and other words through principal component analysis. For instance, 'Vertisols' were associated with 'cracks' or 'Andosols' with volcanoes as their embeddings were similar.

The novelty of work lies in applying NLP technique to soil science publications for evidence synthesis. This manuscript is not foreseen to demonstrate the latest and most advanced NLP techniques but rather to offer a practical view and demonstrate their potentials and limitations in a soil scientific context. We put special emphasis on the methodology used and its ability to recover information rather than interpreting the results themselves. We redirect the reader to chapters 1, 2 and 3 for detailed interpretation of the evidence synthesis. Overall, the objectives of this paper are (1) to demonstrate the potential of natural language processing as for the collection of structured information from scientific publication, (2) to illustrate the ability of topic classification to classify new paper as relevant to a given topic and (3) to assess the ability of natural language processing to extract relationships between given driver (tillage, cover crops, amendment, . . .) and soil variables (hydraulic conductivity, aggregate stability, . . .) based on abstracts.

7.2 Materials and methods

7.2.1 Text corpora

This work used two corpora (sets of texts) which are referred to in the following as the OTIM and the Meta corpuses. The OTIM corpus is related to OTIM-DB (Koestel et al., in prep) which is a meta-database extending the one analyzed in Jarvis et al. (2013) and Jorda et al. (2015). OTIM-DB contains information about the near-saturated hydraulic conductivity obtained from tension-disk infiltrometer between 0 and -10 cm tension (see Koestel et al., in prep. for more information). The meta-database also includes metadata on the soil (texture, bulk density, organic carbon content, WRB classification), 23 climatic variables that were assigned based on the coordinates of the measurement locations, among them annual mean temperature and precipitation, methodological setup (disk diameter, method with which infiltration data is converted to hydraulic conductivity, month of measurement) and land management practices (land use, tillage, cover crops, crop rotation, irrigation, compaction). All data in OTIM-DB were manually extracted by researchers from 172 source-publications. The collected data was then cross-checked by another researcher to catch typos and misinterpretations of the published information. The Meta corpus contained the abstracts of primary studies included in the meta-analyses by Jarvis et al., (in prep.) investigating how soil water infiltration is influenced by soil management practices This Meta corpus contains 1469 publications and hence is larger than the OTIM corpus. The information given in this corpus was not available in a meta-database. Therefore, the validation step had to be carried out by manually extracting information from a subset of the abstracts in this corpus. The references for both, the OTIM and the Meta corpus are available on the GitHub repository of this project.

7.2.2 Extracting plain text from the PDF format

For both corpora, all publications were retrieved as PDF files. The software “pdftotext” (`https://www.xpdfreader.com/pdftotext-man.html`) was used to extract the text from these PDFs. The text extraction worked well apart from one exception where the extracted text contained alternating sentences from two different text columns, making it unsuited for NLP. Other methods were tested, such as the use of the Python package PyPDF2 or the use of the framework pdf.js but did not provide better results than pdftotext. The difficulty of this conversion lies in the PDF format itself that locates words in reference to the page and hence loses the fact that words form sentences and paragraphs. Recovery methods (such in pdf.js or pdftotext) use the distance between words to infer if they belong to the same sentence and detect paragraphs. This makes extracting text from PDF harder for algorithms and is clearly a major drawback of this format. This could be potentially alleviated by using online full-text HTML as source instead of PDF. However, because online HTML full-texts were not available for all documents and the PDF format is the most widespread for exchanging scientific publication, we decided to pursue the analysis with the PDF formats. From the extracted full-texts, abstract and references sections were removed and only the body of the text was used to form the documents for each corpus.

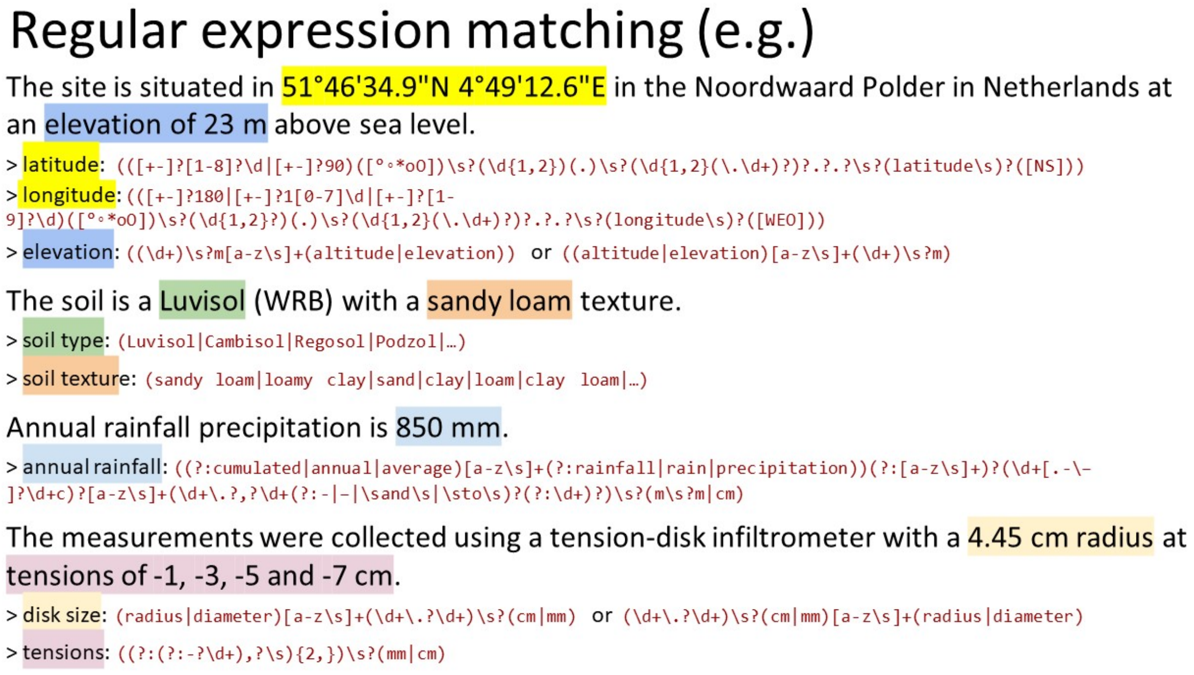
7.2.3 Topic modeling

Topic modeling creates topics from a corpus by comparing the similarity of the words between documents. In this study, each document was composed of bigrams (groups of two words that appear consecutively more than 20 times in the document). We found that using bigrams instead of single words help to get more coherent topics. For instance, the bigrams ‘cover crops’, ‘conventional tillage’ are more informative than ‘cover’, ‘crops’, ‘conventional’ and ‘tillage’ alone. Bigrams that appeared in more than 20 documents but in less than 50% of documents were kept. Topics were created to be as coherent as possible using a latent dirichlet algorithm (LDA). A number of different coherence metrics exist Röder et al. (2015). In this work, the LDA implementation of the *gensim* library (v4.1.2) was used with the CV coherence metric. This CV coherence metric is a combination of a normalized pointwise mutual information coherence measure, cosine vector similarity and a boolean sliding window of size 110 as defined in Röder et al. (2015). The metric ranges from 0 (not coherent at all) to 1 (fully coherent). To define the optimal number of topics to be modeled, we iteratively increase the number of topics from 2 to 30 and look at the averaged topic coherence. Based on this optimal number of topics, the composition of each topic was further analyzed using the pyLDAvis package (v3.3.1) which is based upon the work of Sievert and Shirley (2014). The topic modeling was applied on the Meta corpus given the larger number of documents in this corpus.

7.2.4 Rules-based extraction

Regular expressions are predefined patterns that can include text, number and symbols. For instance, if we are looking for the disk-diameter of the tension-disk infiltrometer, the regular expression ‘`(\d+\.\d)cm\sdiameter`’ will match ‘5.4 cm diameter’. In this regular expression, `\d` means a digit, `\s` a space, `\d+` one or more digit and parentheses are used to enclose the group we want to extract. Regular expressions are a widely used rule-based extraction tool in computer science. They have a high precision but their complexity can quickly increase for more specific topics. Figure 7.1 provides examples of regular expressions used in this work. It can be observed that regular expressions for geographic coordinates are quite complex as they need to account for different scenarios such as decimal format (24.534 N) or degree-minute-second format (24ř4’23.03” N) for instance. In contrast, specific well-defined terms such as World Reference Base (WRB) soil types were easier to retrieve as their wording is unique in the text. Soil textures were likewise easy to extract but less well-defined as e.g. WRB soil types. Often, terms used to describe soil texture of an investigated field site were used to refer to general cases or unrelated field sites in the same text. This made it more challenging to automatically extract information on the investigated site using regular expressions. To complicate matters, soil textures are not always given in the USDA (United States Department of Agriculture) classification system, which can be regarded as a standard for soil. For the sake of simplicity, we did not attempt to identify the texture classification system but treated all textural information as if they were using the USDA system. When gathering information on tension-disk diameters, attention on the length units needed to be paid as well as whether the radius or the diameter is reported. In these more complex cases, the regular expressions were iteratively modified to extract the greatest amount of information from the available papers. For tensions applied, only the maximum tension recovered was used to compute the metrics.

To assess the quality of the extraction, different metrics were used (Figure 7.2). For rules-based extraction, two tasks were required by the algorithm: selection and matching. The selection task aimed to assess the ability of the algorithm to extract relevant information from the text. The matching task assessed the ability of the algorithm to extract not only the relevant, but also the correct specific information as recorded in the database used for validation. For instance, if the NLP algorithm identified “Cambisol” as the soil group for a study conducted on a Cambisol, both, the selection was true positive (TP) and the matching was true. If the text did not contain any WRB soil type and the NLP did not return any, both selection and matching performed well with the selection being a true negative (TN) case. Eventually, when the NLP algorithm did not find a WRB soil type, but the database listed one, the selection was referred to as false negative (FN) and the matching as false. The opposite case, with a soil type found in the text but no entry in the database was called false positive (FP) and the matching was equally false. Eventually, there were cases where the NLP algorithm retrieved incorrect information but still provided a meaningful value, e.g. if the algorithm extracted ‘Luvisol’ as the soil type while the correct value was ‘Cambisol’. Then the selection task was still successful since the found term represents a WRB soil type. However, the matching task failed. Such cases were still marked as false positives, but with a false matching.



Regular expression matching (e.g.)

The site is situated in 51°46'34.9"N 4°49'12.6"E in the Noordwaard Polder in Netherlands at an elevation of 23 m above sea level.

> latitude: `(([+-]?[1-8]?\d|[+-]?90)([°◦*oO])\s?(\d{1,2})(.)\s?(\d{1,2}(\.\d+)?)?.?.?\s?(latitude\s)?([NS]))`

> longitude: `(([+-]?180|[+-]?1[0-7]\d|[+-]?[1-9]?\d)([°◦*oO])\s?(\d{1,2}?)(.)\s?(\d{1,2}(\.\d+)?)?.?.?\s?(longitude\s)?([WEO]))`

> elevation: `((\d+)\s?m[a-z\s]+(altitude|elevation))` or `((altitude|elevation)[a-z\s]+(\d+)\s?m)`

The soil is a Luvisol (WRB) with a sandy loam texture.

> soil type: `(Luvisol|Cambisol|Regosol|Podzol|…)`

> soil texture: `(sandy loam|loamy clay|sand|clay|loam|clay loam|…)`

Annual rainfall precipitation is 850 mm.

> annual rainfall: `((?:cumulated|annual|average)[a-z\s]+(?:rainfall|rain|precipitation))(?:[a-z\s]+)?(\d+[.-\-]?\d+c)?[a-z\s]+(\d+\.?,?\d+(?:-|–|\sand\s|\sto\s)?(?:\d+)?)\s?(m\s?m|cm)`

The measurements were collected using a tension-disk infiltrometer with a 4.45 cm radius at tensions of -1, -3, -5 and -7 cm.

> disk size: `(radius|diameter)[a-z\s]+(\d+\.?\d+)\s?(cm|mm)` or `(\d+\.?\d+)\s?(cm|mm)[a-z\s]+(radius|diameter)`

> tensions: `((?:(?:-?\d+),?\s){2,})\s?(mm|cm)`

Figure 7.1: Examples of different regular expressions used for information extraction. `\d` represents a digit, `\s` a space, `.` (a dot) an unspecified character, `[a-z]` all lower case letters and more generally squared brackets are used to denote the list of characters (for e.g. `[ř*oO]` is used to catch the symbol of degree in latitude/longitude). A character can be “present once or absent” (`\d\.?\d?` will match both integers and decimal numbers), “present at least once” (`\d+` will match `7`, `73` and `735`) or “present a given number of times” (`\d{1,2}` will match `7` and `73` but not `735`). Parentheses are used to segment capturing groups and can also contains boolean operator such as OR denoted by | which is used to catch exact WRB soil name in `(Luvisol | Cambisol | ...)`. Non-capturing parentheses are denoted with `(?:)` like for the regular expression of tensions. The content inside non-capturing parentheses will not be outputted as results of the regular expression in contrast to other parenthesis groups.

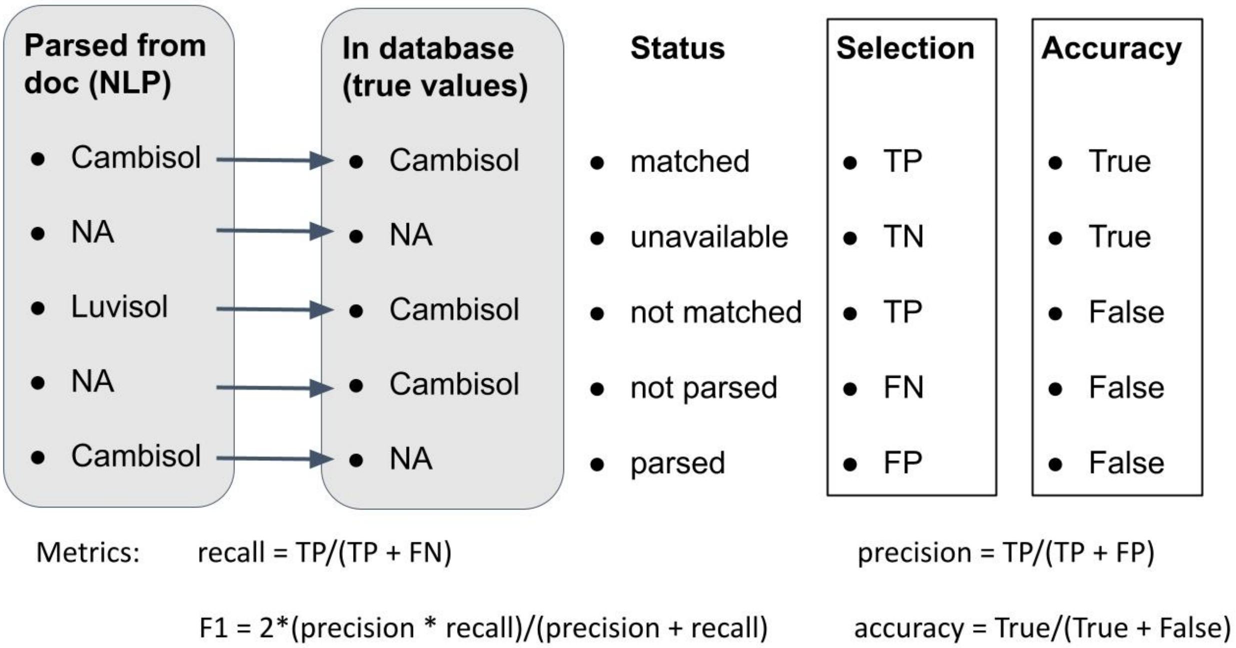


Figure 7.2: Cases of NLP extraction results in regards to the value entered in the database (considered the correct values) for the selection task and the matching task. TP, TN, FN, FP stand for true positive, true negative, false negative and false positive, respectively. The recall, precision, F1 score and accuracy values served as metrics for each task.

Four different metrics were used to evaluate the results: the recall, the precision, the F1 score and the accuracy. The recall assessed the ability of the algorithm to find all relevant words in the corpus (recall = 1). The precision assessed the ability of the algorithm to only select relevant words (precision = 1). If there were 100 soil types to be found in the corpus and the algorithm retrieved 80 words of which 40 were actually soil types, the recall was 40/100 = 0.4 and the precision was 40/80 = 0.5. The F1 score brought the recall and precision in one metric which was equal to 1 if both recall and precision were equal to 1.The recall, precision and F1 scores were used to assess the ability of the algorithm to extract relevant information from the text. Figure 7.3 gives a graphical overview of the recall and precision metrics. In addition to these metrics, an accuracy score was used to illustrate how many NLP extracted values actually matched the one manually entered in the database. Considering the example above, if out of the 40 correctly selected soil types, only 20 actually matched what was labeled in the document, then the accuracy score was 20/100 = 0.2. Figure 7.3 also includes the equations for recall, precision, F1 score and accuracy. Note the difference between precision and accuracy: the precision expresses how many relevant words were extracted while the accuracy quantifies the fraction of words corresponding to the correct information.

All rules-based extraction were applied on the OTIM corpus as information from the OTIM-DB was used for validation. In addition to the above extraction rules, we also identified agricultural practices mentioned in the publications and their co-occurrence within the same publications. This enabled us to highlight which practices are often found together in a study (whether they are opposed or not). To identify management practices in the OTIM corpus, the list of keywords from the Bonares Knowledge Library (`https://klibrary.bonares.de/soildoc/soil-doc-search`). Given that several keywords can relate to the same practice, the list was further expanded by using the synonyms available from the FAO thesaurus AGROVOC (Caracciolo et al., 2013).

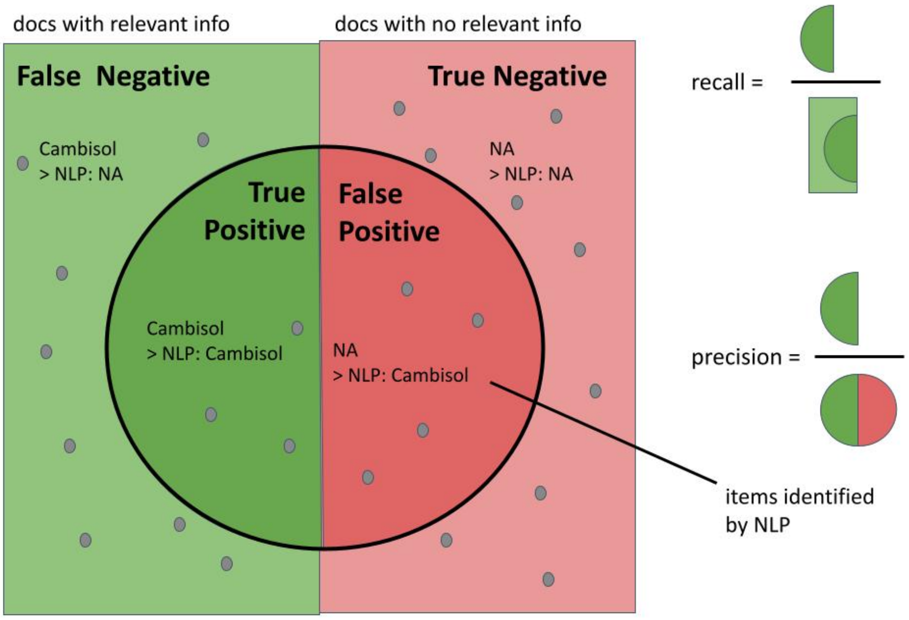


Figure 7.3: Schematic representation of precision and recall. Recall aims to assess how much relevant information was selected out of all the ones available in the database while precision aims to assess how much relevant information was in the selection.

7.2.5 Extracting relationships

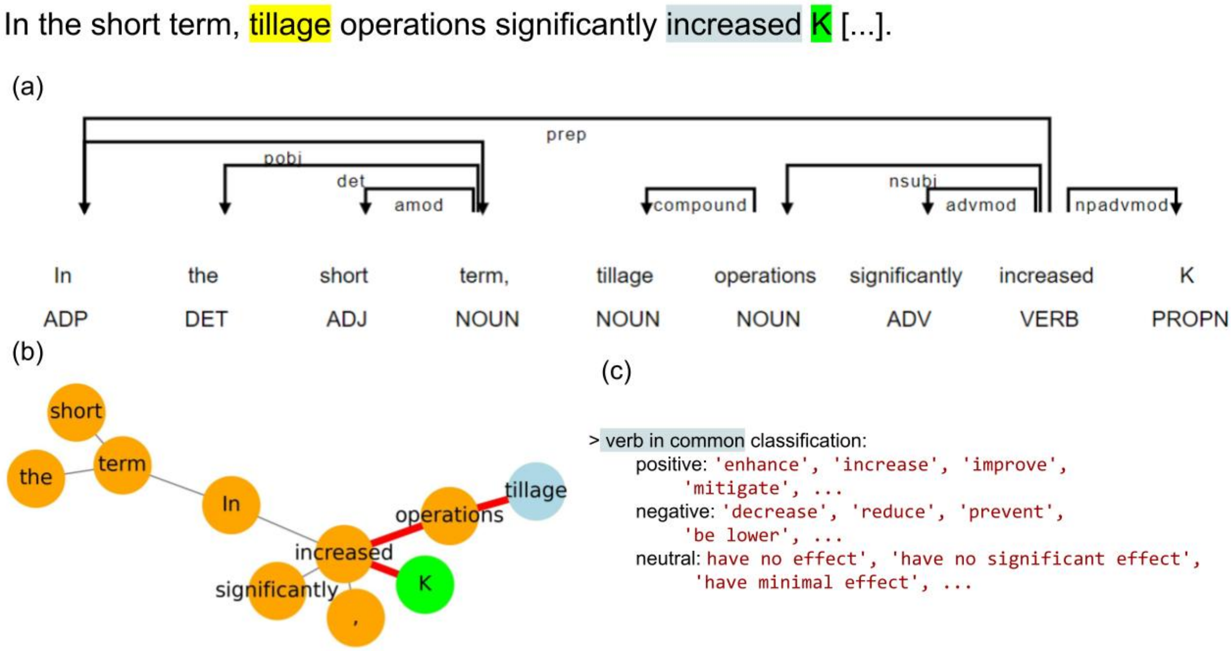
Relationship extraction relates drivers defined by specific key terms to variables. For both drivers and variables. In this study, examples for drivers were 'tillage', 'cover crop', or 'irrigation'. Among the investigated variables were 'hydraulic conductivity', 'water retention' or 'runoff'. These keywords were chosen to correspond to the initial search done to build the Meta corpus (WP3T1). To allow catching both plural and singular form, all drivers and keywords were converted to their meaningful root: their lemma (e.g. 'residues' lemma is 'residue'). Table 7.1 lists the lemma of all drivers and variables considered.

The relationship extraction algorithm searched in the Meta corpus of abstracts for sentences which contained lemmas of both, drivers and variables. Each sentence was then tokenized and each token was assigned a part-of-speech (POS) tag (e.g. noun, verb, adjective). Dependencies between the tokens were also computed. Using these dependencies as links, a graph with one node per token was built. The nodes corresponding to the driver and variables were identified and the shortest dependency path between them was computed (Figure 7.4).

All tokens that were part of this shortest dependency path between the driver token and the variable token were kept in a list. From this list, the tokens containing the driver/variables were replaced by the noun chunk (=groups of nouns and adjectives around the token) as important information can be contained in this chunk. For instance the driver token "tillage" was replaced by its noun chunk "conventional tillage". The list of tokens that constituted the shortest dependency path always included the main verb linking the driver and the variable token. This verb depicted a positive, negative or neutral correlation between the driver and the variable. Other modifiers such as negation marks or other modifiers that can be part of the noun chunk (e.g. 'conservation' or 'conventional' with the noun 'tillage') were also searched for in each sentence. In cases where a positive correlation was

Table 7.1: List of drivers and variables used in the relationships extraction.

Drivers	**Variables**
agroforestry	aggregate stability
biochar	aggregation
catch crop	available water
compaction	bulk density
cover crop	earthworm activity
fertilizer	earthworm biomass
intercropping	faunal activity
irrigation	faunal biomass
liming	hydraulic conductivity
compost	infiltration
manure	infiltration rate
residue	K
tillage	K(h)
traffic	K0
	Ks
	macroporosity
	microbial activity
	microbial biomass
	organic carbon
	organic matter
	penetration resistance
	rainwater penetration
	root biomass
	root depth
	root growth
	runoff
	soil strength
	water retention
	yield



In the short term, tillage operations significantly increased K [...].

```
> verb in common classification:
    positive: 'enhance', 'increase', 'improve',
        'mitigate', ...
    negative: 'decrease', 'reduce', 'prevent',
        'be lower', ...
    neutral: have no effect', 'have no significant effect',
        'have minimal effect', ...
```

Figure 7.4: Example of NLP extraction on a sentence. (a) shows the part-of-speech (POS) tag below each token and the dependencies (arrows) to other tokens. (b) based on these dependencies a network graph was created and the shortest dependency path between the driver (blue circle) and the variable (green circle) is shown in red. (c) The verb contained in the shortest dependency path was classified into positive, negative or neutral according to pre-established lists.

negated (e.g. “did not increase”, “did not have significant effect on”), the relationship was classified as neutral. Sometimes, the relationship did not relate directly to the correlation between the driver and the variable but rather mention that this relationship was studied in the manuscript. Then, the status of the relationships was set to “study”. To assess the recall and precision of the technique, a subset of 129 relationships extracted was manually labeled.

When identifying driver and variable pairs among abstracts, the case can be encountered where one of the driver/variable is expressed using a pronoun. This makes our keyword-based detection useless. The *neuralcoref* Python package was used to replace the pronouns by their initial form using co-reference. This package uses neural networks to establish a link between the pronoun and the entity it refers to. the pronoun is then replaced by the full text corresponding to the entity. For the Meta corpus, the co-reference substitution did not enable to increase the amount of relevant sentences extracted. It was found that it was because the use of pronouns in the respective abstracts was very limited compared to the full text body of the publications. In addition, the accuracy of the co-reference substitution was not always relevant and substitution errors were more frequent than desired. For these reasons, this step was not applied in the final processing pipeline but it is recognized that this step can be useful for other types of corpora. Automatic relationships extraction using OpenIE was also tried but given the specificity of the vocabulary in the corpus of abstract gave relatively poor prediction.

To ensure reproducibility, all codes used in this project were written down in a Jupyter Notebook. This enabled the results to be replicated and the code to be reused for other applications. The Jupyter Notebook also enabled figures and comments to be placed directly inside the document, hence helping the reader to better understand the code snippets. All notebooks used in this work are

Table 7.2: Examples of relationships identified and their corresponding classified labels. Note that the modifiers present in the noun chunk (e.g. “conservation tillage” or “zero tillage”) and the negation in the sentence were taken into account in the status of the relationship. Some sentences contain multiple driver/variable pairs and, hence, multiple relationships. In such cases, only one of the two was indicated in the table.

Relationship (driver/variable in bold)	**Status**
In the short term, **tillage** operations significantly increased **K** (P <0.05) for the entire range of pressure head applied [...].	positive
In humid areas, soil **compaction** might increase the risk of surface **runoff** and erosion due to decreased rainwater infiltration.	positive
Both tillage treatments were designed to prevent runoff and both increased rainwater penetration of the soil.	negative
After 3 years of continuous **tillage** treatments, the soil **bulk density** did not increase.	neutral
No-tillage increased water conducting macropores but did not increase **hydraulic conductivity** irrespective of slope position.	neutral
A field study was conducted to determine the effect of **tillage**-residue management on earthworm development of macropore structure and the **infiltration** properties of a silt loam soil cropped in continuous corn.	study
Dry **bulk density** , saturated hydraulic conductivity (Ks) and infiltration rate [K(h)] were analysed in untrafficked and **trafficked** areas in each plot.	study

available on GitHub https://github.com/climasoma/nlp/ and in suplementary materials on CurveSpace.

7.3 Results

7.3.1 Topic modeling

Figure 7.5 shows the evolution of the coherence metric with respect to the number of topics. The averaged topic coherence increases up to 6 topics then slowly starts to decrease.

Figure 7.6 (left) shows the frequency of the topic in the corpus (as percentage of documents in the corpus that belong to this topic). The circles are placed according to the first two principal components based on their inter-topic distance computed using the Jensen–Shannon divergence (Lin, 1991). Topics closer to each other are more similar than topics further apart. Figure 7.6 (right) shows the frequency of each bigram in the topic and in the corpus. Topic 1, 3 and 5 were relatively similar and focus mainly on cover crops, residues and conventional tillage. Topic 2 grouped papers that investigated the effect of biochar on water content and microbial biomass. Topic 4 focused on the impact of tillage on aggregate sizes. Topic 6 made mention of meta-analysis studies (though all considered documents were primary studies, not meta-analysis). The left part of Figure 7.6, clearly shows how Topic 1, 3 and 5 were closer to each other and how Topic 4 was away from the group according to PC2.

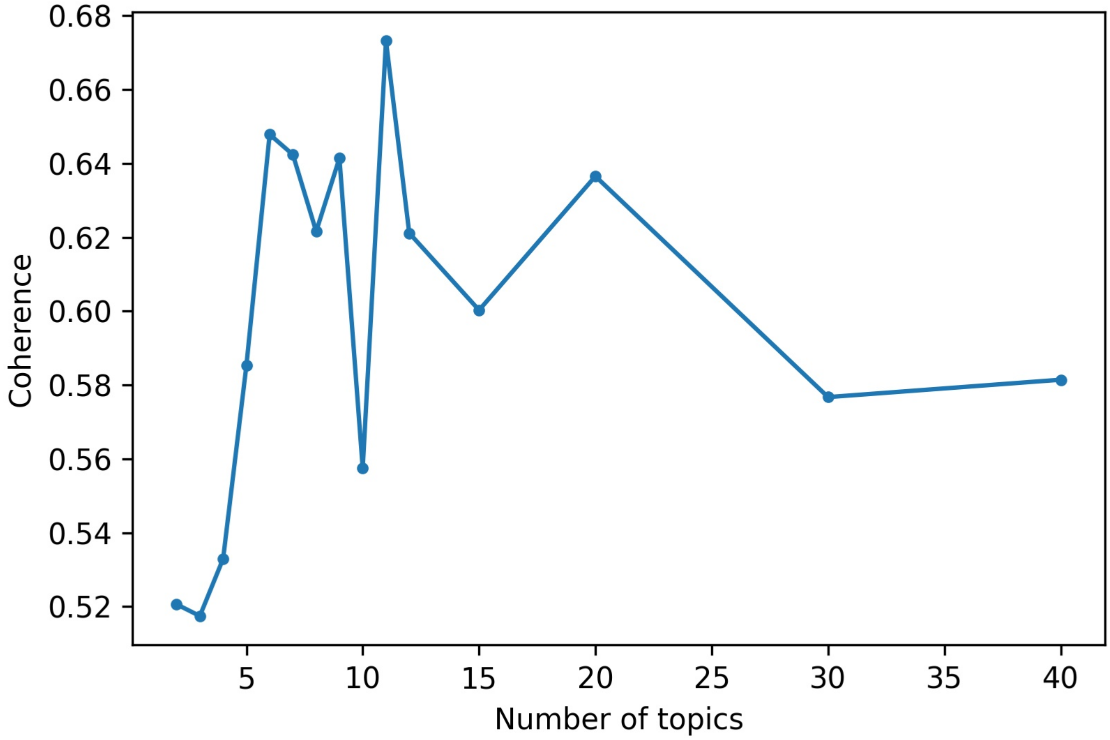


Figure 7.5: Evolution of the averaged topic coherence according to the number of topics chosen to train the LDA model. The coherence metrics is the CV described in Röder et al. (2015) which is a combination of a normalized pointwise mutual information coherence measure, cosine vector similarity and a boolean sliding window of size 110. The error bars represent the standard error of the mean.

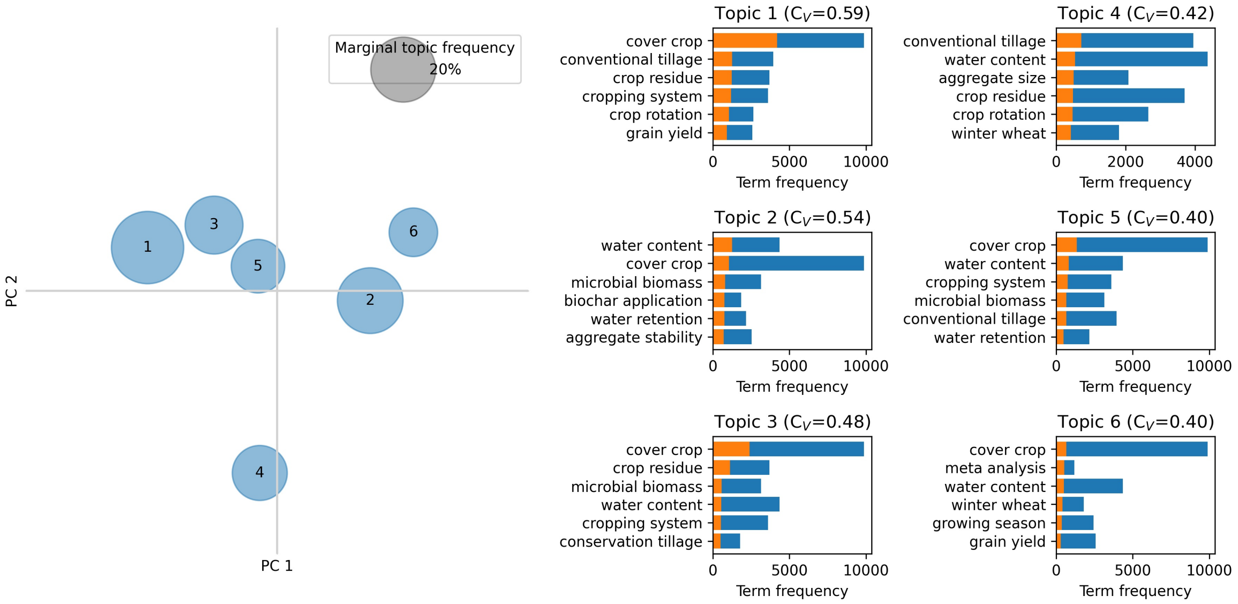


Figure 7.6: (left) Map of topics according to the first two principal components after dimension reduction. (right) For each topic, the 6 more relevant bigrams inside the topic. The orange bars represent the word frequency inside the topic while the length of the full bars (orange + blue) represent the word frequency in the entire corpus. The grey circle represents the size of a topic that contains 20% of the documents of the corpus.

7.3.2 Rules-based extraction

Table 7.3 shows the metrics relative to the different rules-based extraction techniques. Note that "n" does not always represent the number of documents in the corpus as a document can contain multiple locations for instance. Regular expressions associated with a dictionary for soil texture and soil type provided one of the best precision overall due to their high specificity. Soil type had the highest recall, which means that all instances of soil types mentioned in the document had been successfully extracted. Regular expression matching quantities such as ‘rainfall’, ‘disk diameter’, ‘tensions’ or ‘coordinates’ had lower recall than rules making use of a dictionary. Coordinates had a high precision but a lower recall as some coordinate format could not be extracted from the text. This could be partly explained by the conversion of the symbols for degree, minute, seconds from PDF to text. As the encoding of these characters varies a lot between journals, the conversion sometimes led to “ř” converted to “O”, “*” or “0”. Identifying all these different cases while retaining a high accuracy on more frequent cases was challenging with regular expressions.

In addition to extracting specific data, general information about which management practices are investigated in the studies is also important. Figure 7.7 shows the co-occurrence of the detected practices inside the same document as the percentage of documents in the OTIM corpus that contains both practices. For instance, the practice of ’crop residue’ and ‘conversion tillage’ is often found with documents that contain ‘conventional tillage’. ‘herbicide’ is also often mentioned with documents containing ‘crop residue’. Given the small size of the chosen corpus, the co-occurrences are only relevant to the specific field from which they have been extracted; in this case experiments reporting unsaturated hydraulic conductivity from tension-infiltrometer.

Table 7.3: Scores of the rules-based extraction methods. n is the number of items to be extracted. It varies as several coordinates can be provided in the same paper. The method can use only a regular expression (regex) or a combination of regular expression and dictionary (regex + dict.).

Extracted	**Method**	**n**	**Precision**	**Recall**	**F1-score**	**Accuracy**
Soil type (WRB/USDA)	Regex + dict.	174	0.92	1.00	0.96	0.95
Soil texture (USDA)	Regex + dict.	174	0.95	0.88	0.91	0.83
Rainfall	Regex	174	1.00	0.81	0.90	0.89
Disk diameter	Regex	174	0.83	0.66	0.73	0.41
Tensions	Regex	154	1.00	0.56	0.72	0.31
Coordinates	Regex	209	0.92	0.77	0.84	0.73

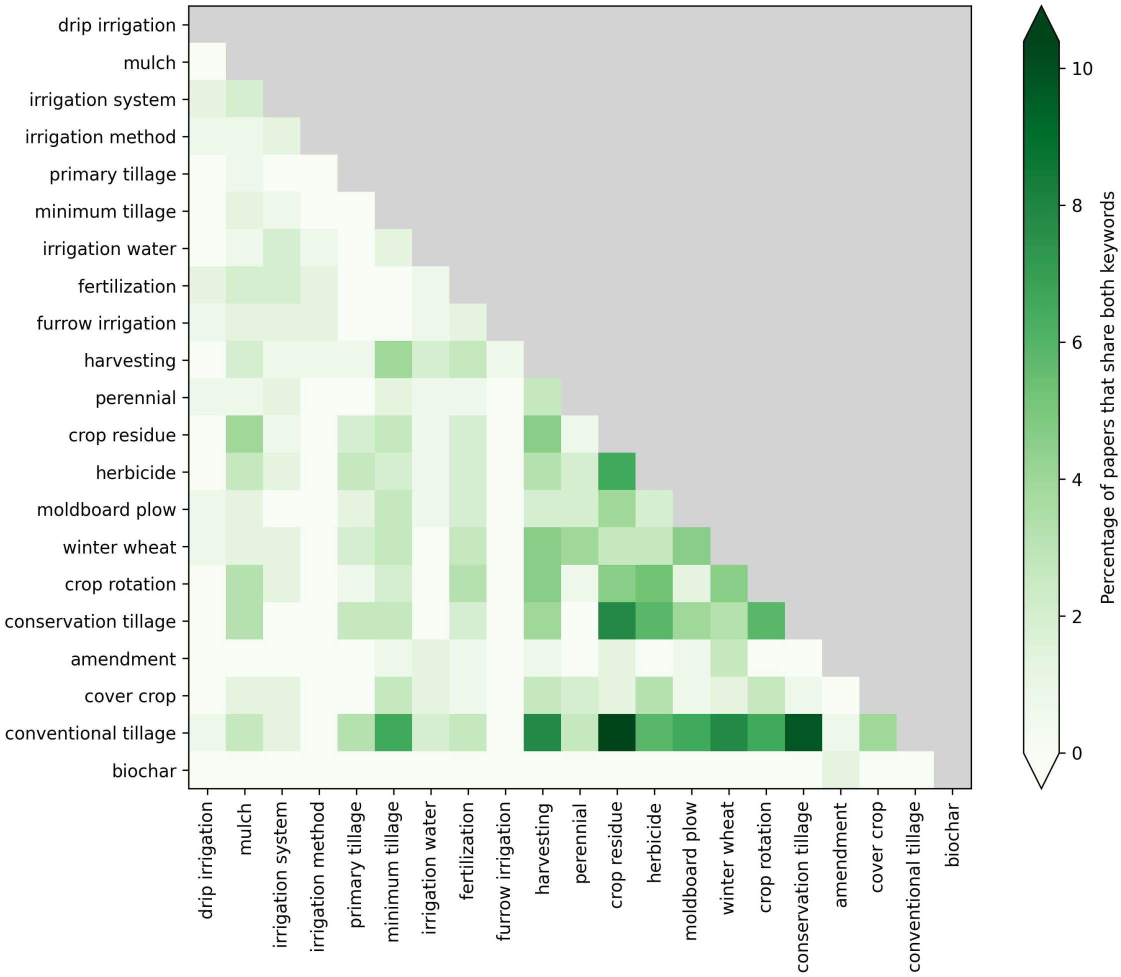


Figure 7.7: Co-occurrence matrix of identified management practices from the OTIM corpus.

7.3.3 Relationship extraction

Figure 7.8 shows the number of relationships from abstracts extracted according to the pair driver/variable identified within them. Relationships including “biochar” or “tillage” as drivers were the most frequent while “yield” was the variable commonly found. Note as well as for some combination of drivers/variables, no statements were available. This helps to identify knowledge gaps within our corpus.

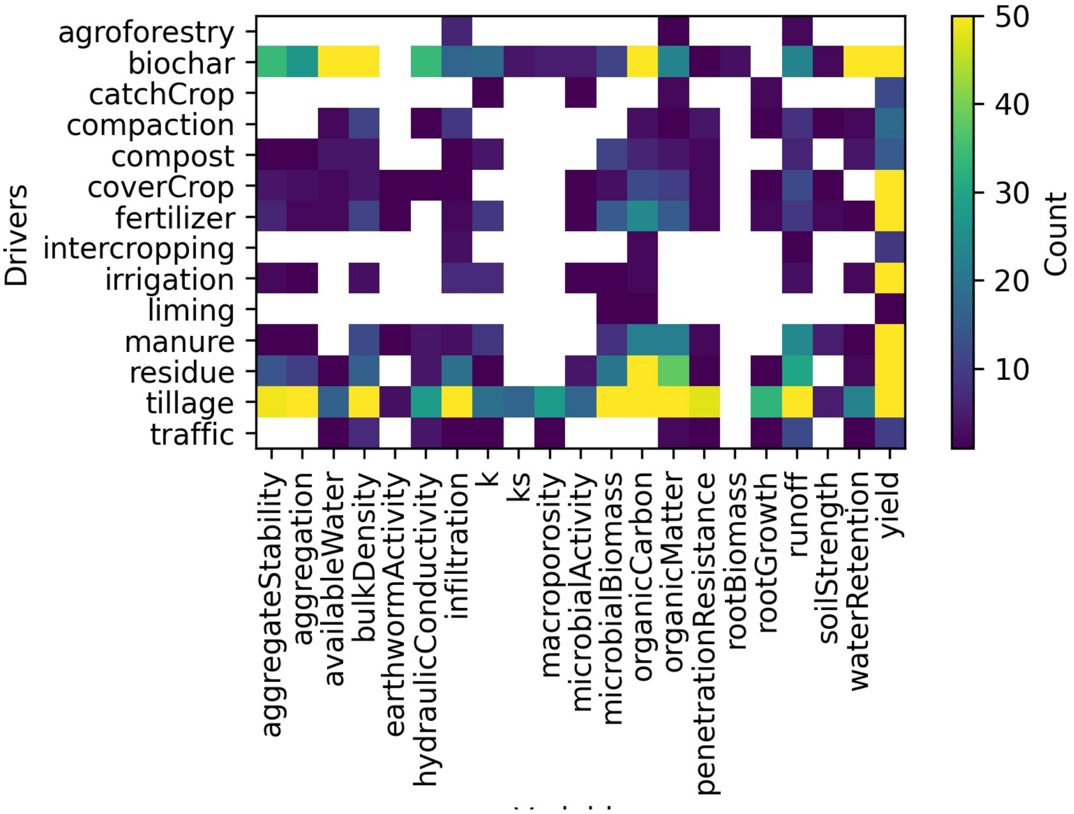


Figure 7.8: Number of relationships identified from abstract according to the pair driver/variable they contain. White cells mean that no relationships were found for the pair inside. Results obtained from the analysis on the Meta corpus.

shows the recall and the precision of the extracted relationships according to their labeled status. For each category (negative, neutral, positive or study), the dark color represents the proportion of relationships correctly identified by the NLP algorithm. The faded color represents the relationships wrongly classified by the NLP or not found at all. Overall, most identified relationships belong to the “study” class. Note as well the larger amount of “positive” relationships compared to “negative” which may be a manifestation of some bias in reporting positive results or at least writing them as positive relationships. The precision of the NLP algorithm is rather high to identify “negative” (precision = 0.99) or “study” (precision = 1.00) classes. In terms of recall, the highest score is achieved for both “positive” and “study” categories.

Based on manually labeled relationships and the ones recovered from NLP, Figure 7.10a offers a detailed comparison according to the number of statements recovered (size of the bubble) and their correlations (colors). Such a figure has the potential to be used to get a quick idea of the relationships present in a large corpus of studies (e.g. for evidence synthesis). It is also comparable to Figure 3 of Chapter 1 which presents a similar layout with the results from the selected meta-

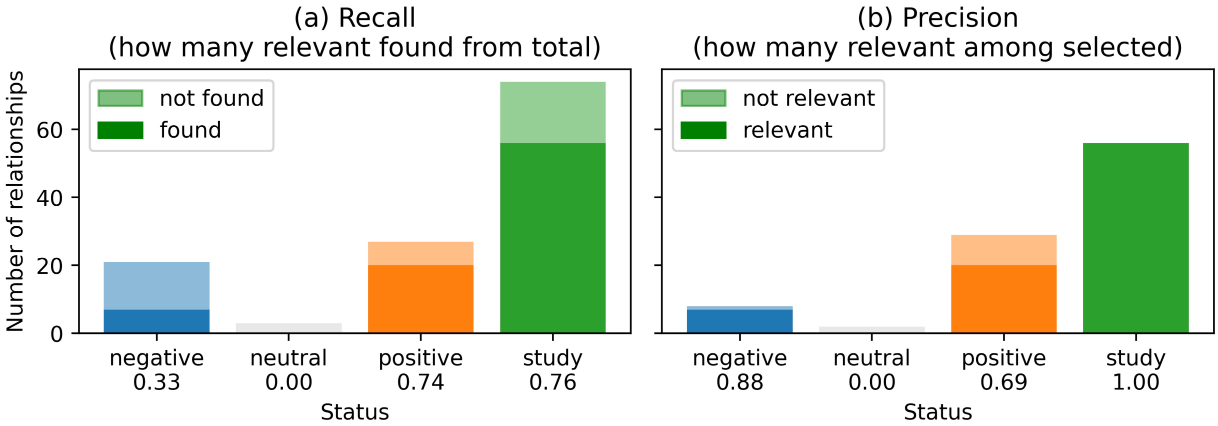


Figure 7.9: Recall (a) and precision (b) of classified relationships extracted from abstracts. Dark color represents the proportion of relationships correctly classified while the faded color represents relationships not found or not correctly classified. The recall and precision metric for each category is given on the X axis. Results obtained on the Meta corpus.

analysis. Note that for a given pair of driver/variable, not all statements have the same relationships and the bubble can contain multiple colors (e.g. biochar/yield, tillage/runoff). Compost is positively correlated to yield, residue is positively associated with lower bulk density and lower run-off, or biochar is negatively correlated to bulk density and positively correlated to microbial biomass. Most of these relationships correspond relatively well to what is reported in meta-analysis (Jarvis et al. in prep.). As demonstrated already in Figure 7.8, the NLP does not recover all relationships perfectly (low recall for negative relationships) and can sometimes be completely wrong (e.g. residue/bulk density). But in two thirds of cases (66%), the relationships are correctly classified.

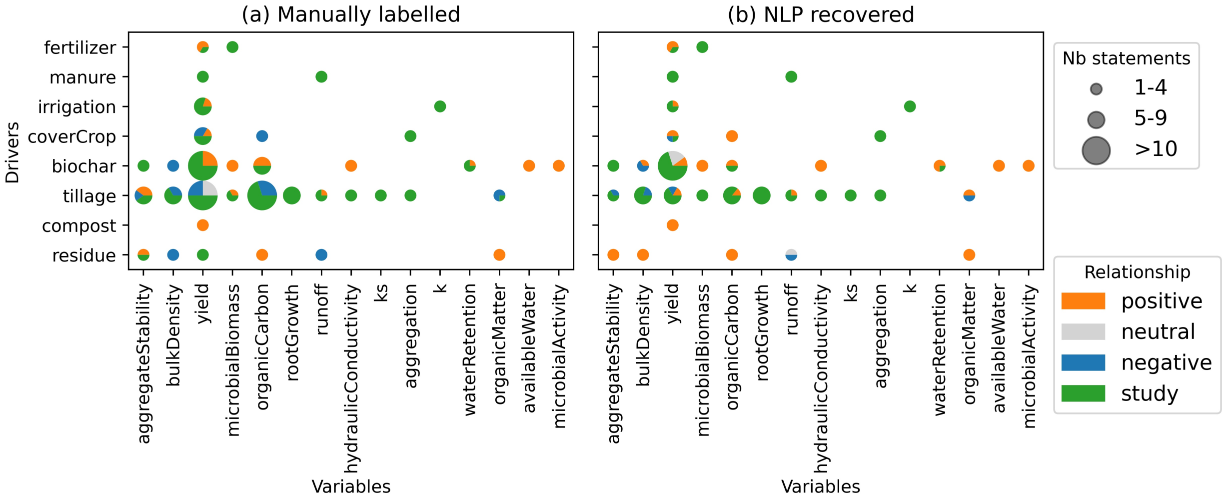


Figure 7.10: Relationships between drivers and variables as (a) manually labelled and (b) recovered by NLP for the Meta corpus.

7.4 Discussion

7.4.1 Topic modeling

One of the first steps of evidence synthesis is to select documents relevant to a given topic. This document selection is usually manually done based on publication title and abstracts. Starting from a first set of documents, a topic model can be used and then further applied on newer publications to see if they could belong to the same topic. Another application of topic modeling is to visualize a pool of research themes within the same topic. In this work, topic modeling was applied to the Meta corpus which contains studies from meta-analysis related to water infiltration and agricultural management practices. Topic modeling helped to identify subtopics within this corpus (Figure 7.6), often related to specific combinations of driver/variables (Figure 7.8 and Figure 7.10). Identifying topics and their frequency within the corpus can also give us information about knowledge gaps or areas less researched.

7.4.2 Rules-based extraction

The NLP methods presented in this paper do not aim at replacing human intervention but rather at supporting them in the repetitive tasks of information extraction from scientific publications. Regular expressions are well suited for this purpose (Table 7.3). While they rarely provide a 100% recall or precision, they can be used to quickly scan a large body of literature and provide a first collection of structured information that can later be manually expanded. However, regular expression needs to be built to be flexible enough to accomodate the various formats found in the publications (e.g. for coordinates) but also discriminant enough to not match irrelevant items. For instance, the regular expression about soil texture catches a lot of terms related to soil texture but not all were related to the soil texture of the actual field site. Applying regular expression on specific parts of the manuscript (for instance, just on the material and methods section), could help improve the precision of the technique.

In addition, information about precipitation, soil texture or applied tensions can be provided in tables. But extracting information from these PDF tables is complex. Indeed, the PDF format does not encode the table as a table but rather as a series of short paragraph and vertical/horizontal lines placed at a given position. When converting the PDF to text, only streams of numbers with more or less regular spacing are found and rebuilding a logical table from it is challenging. Analyzing the regularity of the spacing between these numbers can help in some cases in rebuilding the tables (e.g. Rastan et al. (2019)) but nevertheless understanding what these numbers represent based solely on the headers is for now out of reach of the NLP algorithm. However, recent publications are often provided as an HTML version in which the tables are actually encoded as HTML tables or provided as separate .xlsx, .csv files, hence enabling easier information extraction.

Another difficulty of the conversion from PDF to text is due to the layout of many scientific journals. Text boxes and figures can span multiple text columns and make the conversion difficult (e.g. the figure caption intercalated in the middle of the text). This led Ramakrishnan et al. (2012) to develop LA-PDFText, a Layout Aware PDF to text translator designed for scientific publication. The addition of a hidden machine-friendly text layer in the PDF itself could help the NLP algorithm to better extract information from this format.

7.4.3 Relationship extraction

Relationship extraction based on abstract provides a quick overview of the conclusions from a given set of documents (Figure 7.10). The identification of statements related to a given pair of drivers/variables can already provide some information about potential knowledge gaps (Figure 7.8). However, one important limitation of the approach is that the algorithm can only find the keywords it was told to look for. For instance, no social drivers were found in the statements as there were no keywords associated with it. Social drivers are important to estimate the acceptability of management practices (Chapter 3) and they would gain to be included in the workflow. Another limitation is the fact that the algorithm is limited to what is written in the text. For instance, in Figure 7.8, the token ‘k’, ‘Ks’ and ‘hydraulic conductivity’, all associated with hydraulic conductivity are all extracted by the NLP algorithm as they appear in this form in the abstracts. The use of synonyms can help associate tokens with similar meaning.

The classification of the extracted relationships remains a challenging task and a lot of statements just mention that the pair of drivers/variables has been studied but not the outcome of it (Figure 7.9). That is one of the limitations of the approach as not all information is contained in the abstract. Applying this technique on the conclusion part of a manuscript could help complement the relationships found.

In addition, to confirm that the relationships extracted are well classified a labeled dataset is needed. For this purpose, one has to manually label a given proportion of the statements found and then compare the labels with the NLP finding and iteratively improve the NLP algorithm. This procedure is tedious but needed as general relationships algorithms (often trained on newspaper articles or wikipedia) failed to extract meaningful relationships from field-specific scientific publications. Indeed, a custom NLP algorithm trained on the specific sentence structure and vocabulary encountered in abstracts is more suited to the task. This is in agreement with the conclusions of Furey et al. (2019). However, despite our efforts, the complexity of certain sentences (long sentences with comparison and relative clauses) was too high for our algorithm to reliably detect the relationships between a driver and a variable.

The use of more advanced methods that convert sentences to vectors by the use of transformer networks (e.g. BERT, Koroteev (2021)) can help convert sentences into a numerical vector that carries information about the context of the sentence. Feeded to a deep learning algorithm, these could then provide a deeper understanding of the meaning of the sentence. However, to achieve this larger amount of labeled data will be needed. While a deep understanding of the sentence can certainly help in better classifying drivers/variables relationships, simple regular expressions have already proven to be useful to retrieve specific metadata.

7.5 Conclusion

With the growing body of environmental scientific literature, NLP techniques can help support the needed evidence synthesis. In this work we present examples of three different NLP techniques that can be used for extracting structured information from a large corpus of scientific publications in the domain of environmental sciences. Topic modeling helps to classify existing documents into subtopics and identify less researched topics. It can also be used to assign a new document to a given topic. Both are useful for evidence synthesis. Simple regular expressions helped to retrieve specific information from a corpus of papers on tension.disk infiltrometer measurements, such as coordinates, rainfall, soil types and texture, tension-disk diameter and tensions applied. This technique can be used to build up databases or for evidence synthesis. However, the conversion from the PDF format to text can be a source of mistakes given the complex layout of scientific articles and the non-machine friendly PDF format. While PDF remains a standard, web versions of scientific manuscripts have the potential to relieve this barrier. Finally, based on abstracts, sentences containing a given pair of drivers/variables were identified. The number of relationships identified per pair already provides an insight into what topics are best studied and can be used to identify knowledge gaps. The list of drivers and variables need to be expanded iteratively to be sure that all synonyms can be caught. Using the shortest dependency path between a driver and a variable, their relationship was classified into negative, neutral, positive or ‘study’ (if it was just mentioned that the topic is studied in the paper). While their classification remains challenging and field-specific given the complexity of human language, this approach can already provide a good overview of the main conclusions drawn from a corpus of documents. Overall, topic modeling, regular expression and complex relationships extraction have the potential to support fully automated evidence synthesis that can be continuously updated as new publications become available.

Chapter 8

Conclusion

The CLIMASOMA project aimed to contribute to an alignment of research strategies connecting agricultural management, soil structure and climate adaptation potential through its summary of the literature, its metaanalysis and its identification of knowledge gaps. On the one hand, we focused on soil management and cropping systems, but we also investigated the current understanding of farmers' perception of climate change, its associated risks and opportunities, related EU policy instruments and how this may influence their decisions regarding implementing soil adaptation measures. We also investigated the potential of new research tools such as natural language processing, meta-analysis and machine learning to increase our ability to extract information from existing literature and derive context-specific information from it.

Consensus on effective agricultural practices

There is considerable degree of consensus in the literature on the effects of soil and crop management practices. For three combinations of practices the scientific evidence was particularly clear: continuous living cover, organic amendments and reduced or no-till systems. Maintaining a **continuous living cover** on the soil in space and time is the most effective way to foster soil structure. Such a healthy soil structure is typically better at infiltrating and retaining water. Scientific research on **organic amendments** for agricultural land has focused extensively on the effects of biochar, even though this technique has not (yet) been widely adopted in the agricultural sector. Biochar has a positive effect on soil hydrological functioning. From the few available studies, it is also clear that the addition of organic amendments in general improves soil structure and plant available water and reduces runoff and erosion. The evidence on the effects of **reduced or no-tillage** shows mixed results, with adverse effects on bulk density, despite improvements in soil structure and available water. Both positive and negative effects on runoff have been reported. Although significant trends are visible in the literature, it is still sometimes difficult to differentiate among pedo-climatic regions and other context-specific factors. Many meta-analyses perform little context-specific analyses, so the information is lacking in the final publication. In addition, there is often a lack of information in the original studies used to extract the necessary meta-data. It is therefore important for studies on agro-ecosystems from all disciplines to agree on standards concerning the required meta-data reported in peer-reviewed studies.

Key policy instruments

Public policies play an important role in farmers' decisions influencing sustainability of crop production. A set of economic and regulatory incentives are provided trough the CAP to promote more sustainable soil management and climate change adaption. The understanding and consideration by the farming community of sustainable soil management practices and climate risk management instruments in general and agricultural insurance in particular can be improved. A key opportunity to increase knowledge of the benefits of those systems is offered through rural development training, knowledge transfer and management exchanges initiatives and the inclusion in the farm advisory service, helping farmers to implement appropriate solutions for their specific situations, including aspects of climate change adaptation.

The farmer doesn't exist

The more aware and concerned farmers are about the impacts and risks of climate change the more likely they will adopt an adaptation strategy. Nevertheless, farmers have both climatic and non-climatic reasons to change their practices. 'Multi-purpose' adaptation strategies that cover the many areas of risk and opportunities that a farmer is facing show most potential, since soil-related adaptation strategies were not always the entry point for farmers in the context of climate change adaptation. In addition, the "farmer" as such with his/her particular behaviour does not exist. Grouping farmers in a particular location, based on objective characteristics of their farm in combination with their personal characteristics may help to identify potential underlying factors driving farmers climate change adaptation decision making. The communication of climate adaptation strategies needs to emphasize the connection between extreme weather events and climate change to enhance farmers' understanding of the risks or opportunities that climate change poses. Moreover, we have to communicate to farmers the benefits soil management can bring about in the context of the weather changes they are experiencing directly. Co-learning exchanges between farmers, and with scientists, are key to increase in adopting climate adaptation practices.

Approaches to assess the direct impact of climatic drivers

Field **manipulation experiments** are powerful tools to understand the adaptative response of soils to climate change because they clarify the cause-and-effect relationships in both short- and long-term. The **space-for-time substitution** approach allows to simulate climate change scenarios ranging from current climate to altered temperature (warming) and precipitation regimes (droughts and floods).

For instance, long-term **increase of precipitation** affects soil hydraulic property, by reducing infiltration rate and influencing water retention, especially during dry summer. This can negatively affect microbial abundance and activity. Similarly, also below-ground C and N cycling are highly influenced by changes in precipitation regimes. Particularly, higher precipitation accelerates soil organic matter decomposition, while drought events reduce the decomposition due to the increased physical protection of soil organic matter. Bacterial and fungal communities are less influenced by decreased precipitation. Some manipulation experiments, investigating the combined effects of climatic drivers and enhanced CO_2 concentration on soil properties, highlight that they soil water and microbial processes are directly linked to soil organic matter decomposition.

In general, this synthesis provides a clear overview of the current knowledge on the adaptative response of key soil properties and functioning to climate change based on field approaches. It advances our understanding on the impact of climate drivers and enhanced CO_2 concentration on soil properties and functioning **mainly related to grassland land use**. Overall, more insights need to be obtained for other land use and soil management practices. This is of crucial importance to help us understand the complex mechanisms underlying the responses of soil system to climate change that are still not completely known.

Climatic drivers affect near-saturated hydraulic conductivity

We confirmed **significant correlations between climate variables as well as the elevation above sea level with saturated and near-saturated hydraulic conductivity**. While it seems very likely that these variables influence soil physical properties, the exact underlying mechanisms need to be investigated in future studies. We found indications that specific soil management practices lead to changes in saturated and near-saturated hydraulic conductivities, which were **increased under perennial cultures and decreased for no-till arable fields with annual crops and for compacted soil**. Our data also confirmed that it is fundamental to take the time of the measurement after the last tillage operation into account to understand relationships between soil management and saturated and near-saturated hydraulic conductivity. **All management impacts turned out to be dependent on the pedo-climatic context**, as they only could be observed if variations in the latter were ruled out. We found that the data availability for tension-disk infiltrometer data was too scarce and riddled with too many gaps for detailed analyses of other soil management impacts, more specific pedo-climatic context dependencies and publication bias. Furthermore, we detected **indications that the available data was afflicted with experimenter bias**. Altogether, it was not possible to predict saturated and near-saturated hydraulic conductivities from the available data for new sites, which echoes results of similar attempts to build respective pedotransfer functions. More measurements with better documented meta-data and better suited predictor variables would be needed for progress in this field of research. Studies **quantifying soil structure evolution with respect to season, land use and soil management using X-ray imaging** may turn out to provide useful insight that may point towards for more appropriate proxy variables for the saturated and near-saturated hydraulic conductivity of soil.

Natural language processing helps to extract data from vast amount of literature

At the image of this project, synthesizing a body of scientific literature over a topic and extracting structured information from it remains a task that necessitates at lot of effort and need to be frequently repeated to “keep up” with novelties. As the body of scientific is growing, so is the effect needed to synthetize evidence. While natural language processing methods cannot completely replace human interventions, they can, however, be of great help to extract specific information to build database. They can also help to identify topics among a set of documents and summarize relationships identified between a driver and a variable based on abstracts. Extracting information from PDF format or table remains an obstacle, as well as the manual tuning needed to adjust the algorithm. Overall, natural language processing methods are a great tool to support regularly updated evidence synthesis or large body of literature.

Glossary

Chapter 1

Chapter 2

AECM: Agricultural-Environment-Climate Measures

CAP: Common Agricultural Policy. The set of legislation and practices adopted by the European Union to provide a common, unified policy on agriculture. The initial measures were introduced in 1962. Since then, the policy has been adapted and developed and has undergone a number of reforms.

CSF: Common Strategic Framework, translates the objectives of the Europe 2020 Strategy into workable actions for the 5 European Structural and Investment Funds (ESIF).

Cross-compliance: A system linking most CAP payments to a set of basic standards to ensure the good agricultural and environmental condition of land (GAECs) and certain obligations, known as statutory management requirements (SMRs). SMRs are defined in the respective EU legislation on the environment, climate change, public, animal and plant health, and animal welfare.

Direct payments: Aid granted directly to farmers to provide them a safety net. They mainly take the form of a basic income support, not linked to production. They help to stabilise farmers' income stemming from sales on the markets, which are subject to volatility. Direct payments are made from the European Agricultural Guarantee Fund (EAGF), commonly referred to as 'Pillar I' of the CAP.

ECA: European Court of Auditors

EFA: Ecological Focus Areas. Land on farms dedicated to specific practices or features beneficial for the environment. Under greening, farms generally must dedicate at least 5 % of their arable land to EFAs.

EIP: European Innovation Partnership

ESIF: European Structural and Investment Funds, finance the EU territorial/cohesion policies. The ESIF include five different funds, which are all covered by Regulation (EU) No 1303/2013 of the European Parliament and of the Council, the so-called 'Common Provisions Regulation'. The Structural Funds have two components: the European Regional Development Fund (ERDF), providing financial support for the development and structural adjustment of regional economies, economic change, enhanced competitiveness as well as territorial cooperation throughout the EU; and the European Social Fund (ESF), seeking to contribute to the adaptability of workers and enterprises, access to employment and participation in the labour market, social inclusion of disadvantaged people, combating all forms of discrimination, and creating partnerships to manage reforms in employment. The other three funds constituting the ESIF are the Cohesion Fund, which supports exclusively less-developed Member States; the European Agricultural Fund for Rural Development; and the European Maritime and Fisheries Fund.

EGD: European Green Deal - provide a roadmap for making Europe the first climate-neutral continent by 2050

ESPG: Environmentally Sensitive Permanent Grassland

GAEC: Good Agricultural and Environmental Condition. Collective term for a set of basic standards, applicable under cross compliance, defining good agricultural and environmental condition of land.

PG: The permanent grassland ratio. Ratio of permanent grassland to total agricultural areas

Pillar I of the CAP: Part of the Common Agricultural Policy encompassing direct payments to farmers and market measures.

Pillar II of the CAP: Part of the Common Agricultural Policy encompassing rural development measures.

SMR: Statutory Management Requirements. A collective term for a set of obligations defined in the respective EU legislation on the environment, climate change, public, animal and plant health, and animal welfare, and applicable under cross-compliance.

RDP: Rural development Programme**,** An EU policy, commonly referred to as Pillar II of the CAP, addressing the economic, environmental and social needs of EU rural areas. Rural development payments are made from the European Agricultural Fund for Rural Development (EAFRD), with Member State co-financing.

SOC: Soil Organic Content

Chapter 3

Atl: Atlantic climate risk zone

BMP: Best Management practices

Bus. Diver Business diversity

CC: Climate change

CC & AD: Climate change awareness and Adaptation

CCA: Climate change awareness

CE: Choice experiment

Cont: Continental climate risk zone

Cvs: Cultivars

DLO: Dienst Landbouwkundig Onderzoek

EEA: European Environmental Agency

Env. Respon: Environmentally responsible

EO: Ecologically orientated

FTZ: Farm Type Zone

IB: Innovative behaviour

IPCC: Intergovernmental Panel on Climate Change

LPA: Less productive areas

MPPACC: Model of Private Proactive Adaptation to Climate Change

N: Northern climate risk zone

NCC: Neg CC

No Till: No Tillage

PAE: Perceived adaptation efficacy

PCA: Principal component analysis

PCC: Positive CC

PMT: protection motivation theory

PO: Production orientation

PRM: Profit and resource maximiser

PsCC: Passive CC

S: Southern climate risk zone

SE: self -efficacy

SR: Sceptical regulations

Srg: short rotation, grassland

Chapter 4

C: Carbon

CH4: Methane

CO2: Carbon dioxide

ETa: Actual evapotranspiration

EU: European Union

GHG: Greenhouse Gas

MBC: Microbial Biomass Carbon

MBN: Microbial Biomass Nitrogen

N: Nitrogen

N2O: Nitrous oxide

pCO2: Pressure of CO2

Rs: Soil respiration

SFT: Space-For-Time substitution approach

SOC: Soil Organic Carbon

SOM: Soil Organic Matter

WP: Work Package

Chapter 5

K_s: saturateed hzdraulic conductivity

K_h: saturated or near-saturated hydraulic conductivity in the tension range between 0 and 100 mm

K_x: hydraulic conductivity at tension of x mm, e.g. K_{100}

OTIM-DB: Open Tension-disk Infiltrometer Database

ES: effect size

LGB: light gradient boosting (a machine learning approach)

SHAP: Shapley additive explanations (an index that quantifies the importance of a predictor in a machine
learning approach)

RMSE: root mean squared error

WRB: World reference base

USDA: United States Department of Agriculture

Chapter 6

NLP: Natural Language Processing

WRB: World reference base

USDA: United States Department of Agriculture

LDA: Latent Dirichlet Algorithm

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