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Soil and crop management practices and the water regulation functions of soils: a qualitative synthesis of meta-analyses relevant to European agriculture

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Abstract. Adopting soil and crop management practices that conserve or enhance soil structure is critical for supporting the sustainable adaptation of 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 paper, we evaluate the evidence for this assertion by synthesizing the results of 34 published meta-analyses of the effects of such practices on soil physical and hydraulic properties 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 the effects of soil and crop management in terms of the underlying processes and mechanisms. Finally, we identify how responses to alternative soil–crop management systems vary under contrasting agro-environmental conditions across Europe. 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 practices that maintain "continuous living cover" result in significant benefits 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 these systems is a reduction in soil water storage and groundwater recharge, which may be problematic in dry climates. Some important synergies are reductions in nitrate leaching to groundwater and greenhouse gas emissions for nonleguminous 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 is enhanced under reduced tillage intensity, which should improve soil structure and infiltration capacity and reduce surface runoff and the losses of agro-chemicals to surface water. However, the evidence for these beneficial effects is inconclusive, while significant trade-offs include yield penalties and increases in greenhouse gas emissions and the risks of leaching of pesticides and nitrate.

Our synthesis also highlights important knowledge gaps on the effects of management practices on root growth and transpiration. Thus, conclusions related to the impacts of management on the crop water supply and other water regulation functions are necessarily based on inferences derived from proxy variables. Based on these knowledge gaps, we outlined several key avenues for future research on this topic.

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1 Introduction

As a consequence of ongoing climate change, the occurrence of extreme weather events (i.e., heat waves, summer droughts, waterlogging and flooding) such as those experienced during the recent summers of 2018, 2021 and 2022 will almost certainly increase in all parts of Europe (IPCC, 2021; AgriAdapt, 2017). Climate change impacts on agriculture are projected to result in an average 1 % loss of gross domestic product by 2050 but with large differences among regions and farming systems (Jacobs et al., 2019). An urgent task is therefore to develop guidance on soil and crop management practices that would help farmers in all regions of Europe adapt to these extreme weather situations.

The ecosystem services a soil can deliver depend profoundly on its structure, which we define here as the spatial arrangement of the soil pore space. Mediated by various biological (e.g., faunal and microbial activity) and physical processes (e.g., traffic compaction and wet–dry and freeze–thaw cycles), soil structure is constantly evolving at timescales ranging from seconds to centuries, driven by weather patterns as well as changes in climate and land management practices (Fig. 1). In turn, soil structure strongly affects all life in soil and the balance between infiltration and surface runoff, as well as drainage and soil water retention and therefore the supply of water and nutrients to crops. Agricultural practices can affect soil structure directly (e.g., compaction due to use of heavy machinery) or indirectly (e.g., improved soil structure through increased bioturbation by earthworms after addition of organic matter to the soil). Practices commonly adopted in "conservation agriculture" (Palm et al., 2014) are thought to enhance soil structure and should therefore help to maintain agricultural production in the face of severe droughts or heavy rain. 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. Other more recently coined and partially related terms are "regenerative agriculture", which acknowledges past failures to preserve soil health (Schreefel et al., 2020) and "climate-smart agriculture", which is defined by Office of Assistant Director-General (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 has especially been the case in the last few years (Beillouin et al., 2019a, b), 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 analyses. Indeed, the increase in the number of meta-analyses published on topics related to conservation agriculture has been so dramatic that four over-arching syntheses of these meta-analyses have also recently been published. Bolinder et al. (2020) evaluated the effects of organic amendments and cover crops on soil organic matter (SOM) storage, while Schmidt et al. (2021) focused on the effects of biochar on crop performance. Beillouin et al. (2019b) and Tamburini et al. (2020a) carried out even more ambitious and comprehensive reviews of meta-analyses of the effects of conservation agriculture and crop diversification strategies on a wide range of ecosystem services. Tamburini et al. (2020a)

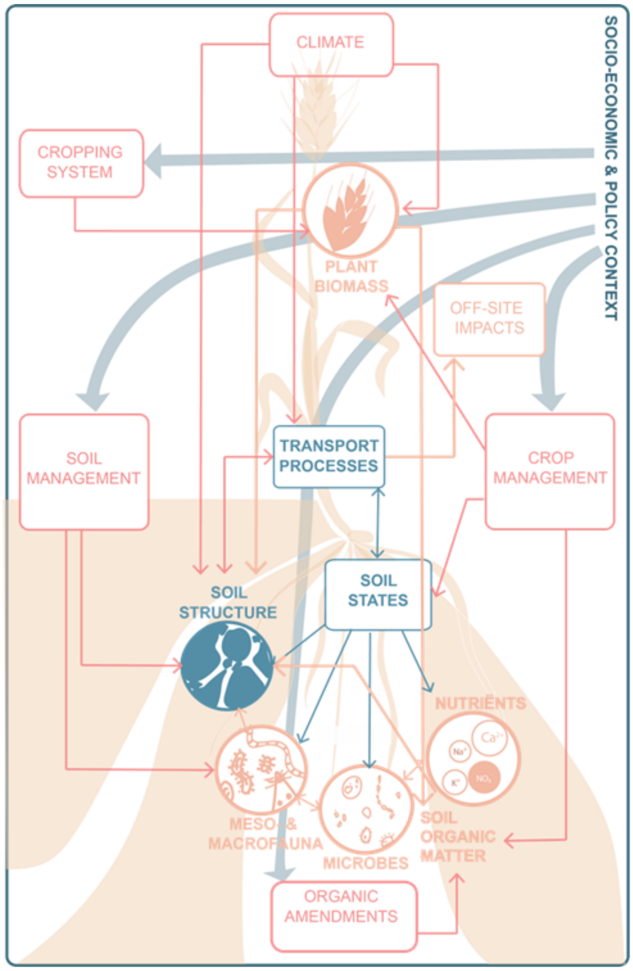

Figure 1. Schematic diagram of drivers, agents and processes governing the dynamics of soil structure and its effects on the soil–plant system.

concluded that diversification practices most often resulted in a "win–win" situation for ecosystem services including crop yields but that the 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 their broad-brush treatment. These previous syntheses of meta-analyses on the benefits of conservation agriculture have placed very little emphasis (Tamburini et al., 2020b) or none at all (Bolinder et al., 2020; Beillouin et al., 2019b, a) on soil hydrological functioning, even though this is key for climate change adaptation. In their synthesis, Tamburini et al. (2020a) included 17 meta-analyses (involving 31 effect-size comparisons) relevant to water regulation, but most of these concerned water quality issues rather than hydrological functioning per se. Beillouin et al. (2019b) 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 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. In those cases where the information is available, we summarize knowledge of context-specific effects of relevance for the range of agro-environmental conditions found in Europe 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 behavior) and will enable practitioners and policymakers to draw context-specific conclusions concerning the efficacy of management practices as climate adaptation tools. This study highlights where consensus has been established on practices improving the water regulation function of soil that are meaningful for climate change adaptation. We also identify remaining knowledge gaps and key avenues for future research.

2 Materials and methods

2.1 Literature search and data extraction

The text string shown in Fig. 2 was used to search the published literature using Web of Knowledge in May 2021. This search returned 663 results. 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 were not retained. Our search identified 34 relevant meta-analyses focusing on the effects of soil and crop management on soil physical properties and hydrological processes using effect ratios (Appendix B). Figure 3 shows the number of primary studies per publication year included in the 34 meta-analyses. A peak is clearly visible in 2014, which is explained by the fact that all 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 variables (e.g., microbial biomass), since these help to explain the observed effects on physical/hydraulic properties and hydrological processes, as well as other studies that analyzed target variables representing potential trade-offs or synergies. Among these, we focused primarily on the impacts of management practices on crop yields, greenhouse gas emissions and water quality. An additional 127 published meta-analyses of this kind were identified by our literature search. These studies are listed in the supplementary file ("Supporting studies.xlsx").

The target variables (e.g., soil physical and hydraulic properties) and drivers (i.e., soil and crop management practices) included in the 34 meta-analyses were then classified into a limited number of groups. The target variables were grouped into five classes: pore space properties (e.g., porosity and bulk density), hydraulic properties (e.g., saturated hydraulic conductivity and field capacity), mechanical properties (e.g., soil aggregate stability and penetration resistance), water flows (e.g., infiltration, surface runoff and drainage) and plant properties (e.g., root length density and water use efficiency). Likewise, the management practices were also grouped into five classes: soil amendments (e.g., manure, biochar and organic farming systems), cropping practices and systems (e.g., cover crops and crop rotations), tillage systems (e.g., no-till), grazing management and irrigation.

2.2 Quality assessment

We performed a quality assessment of the selected 34 meta-analyses using 15 of the criteria proposed by Beillouin et al. (2019a). Figure 4 presents a summary of the quality of the selected meta-analyses according to these criteria. Nearly half of the meta-analyses included datasets in the paper, while only ca. 44 % investigated publication bias (Philibert et al., 2012). The authors of these studies used simple statistical techniques such as frequency distributions of effect sizes or "funnel plots" of sample sizes against effect sizes to investigate whether experiments with nonsignificant effects are underrepresented in the literature. For both of these methods, symmetry of the distributions is taken to indicate a lack of bias. Two studies detected evidence of publication bias (Shackelford et al., 2019; Basche and deLonge, 2019) using this method, although in both cases the effects on the overall conclusions of the studies were considered marginal. Basche and deLonge (2019) also investigated the sensitivity of the outcome to the exclusion of individual studies, which is another important aspect of publication bias. They found robust results for the impacts of no-till and cover crops on infiltration.

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. Search string used to identify relevant meta-analyses.

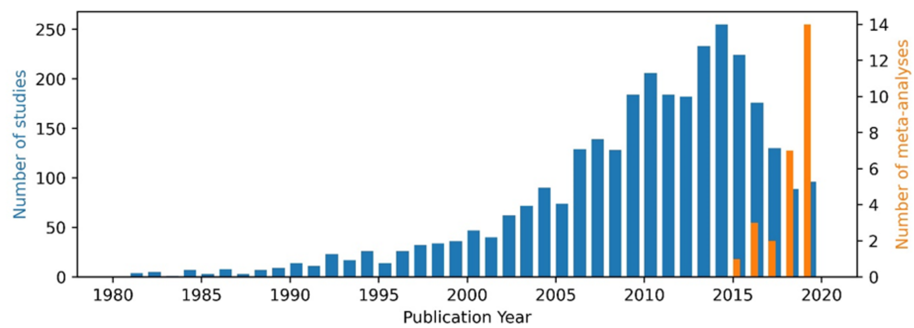

Figure 3. Number of primary studies included in the 36 selected meta-analyses published per year and the publication year of these meta-analyses.

2.3 Redundancy analysis

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. (2019a). For each of the 34 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, so we had to manually check these references based on contextual information supplied in the supplementary material. In most cases, however, the title was provided in the meta-analysis, and the DOI could be extracted automatically from the Crossref database. We then manually checked if the title of the paper matched the one found on Crossref, to confirm the DOI assignment. The results of the redundancy analysis are presented in Appendix A as well as in the notebook at https://github.com/climasoma/review-of-meta-analyses/blob/main/notebooks/redundancy.ipynb, last access: 22 December 2022. The main outcome of this analysis is that redundancy is only problematic for a few meta-analyses on biochar that were published almost simultaneously (Edeh et al., 2020; Rabbi et al., 2021).

2.4 Qualitative analysis of effect sizes

In total, the 34 meta-analyses reported 104 effect ratios comparing the impacts of a management practice to a control

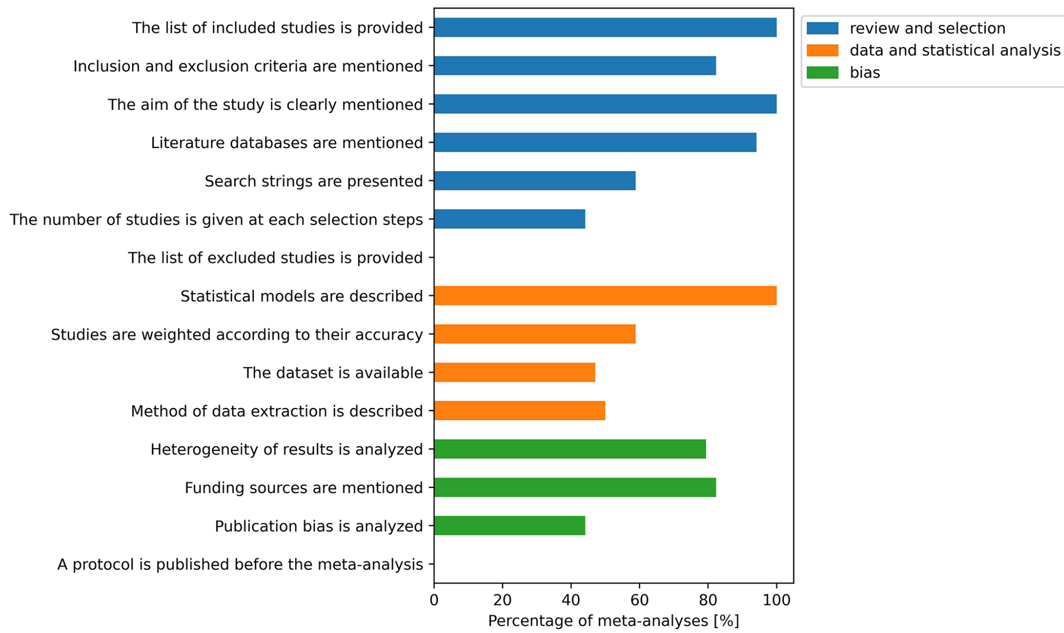

Figure 4. Proportion of the quality criteria defined by Beillouin et al. (2019a) that are met by the selected meta-analyses in this study.

treatment for a particular response variable. The overall effects of these treatments on the target variables (either positive, negative or neutral, i.e., nonsignificant) were read from tables and figures in each of the 34 meta-analyses and analyzed in a qualitative way. This is because we do not have access to the individual effect sizes in all the primary studies included in the meta-analyses (see Sect. 2.2 "Quality assessment"). We considered the effect as "positive" if the average log response ratio and the entire 95 % confidence interval reported in the meta-analysis were larger than zero (equivalent to a response ratio of 1 prior to taking logarithms). If part of the 95 % confidence interval for the log response ratio overlapped zero, the effect was considered "neutral". If the entire confidence interval was smaller than zero, the overall effect was considered "negative". The directions of the effect sizes are therefore purely statistical and have no connotation of value. We report the effects in a statistical sense because in some instances it would not be clear whether effects would be beneficial or detrimental. It should also be noted that positive or negative overall effects derived collected from a given meta-analysis do not imply that all the individual effects in the primary studies included in this meta-analysis necessarily pointed in the same direction. For all overall effects retrieved, we also noted the number of individual effects from the primary studies used to compute the overall effect reported in the meta-analysis.

3 Results and discussion

Figure 5 summarizes the statistical relationships found between the drivers and target variables in the selected meta-analyses. It shows that the effects of cropping systems, tillage, organic amendments and, to a lesser extent, irrigation management have been studied extensively. These topics are discussed in the following sections. It is equally interesting to consider the empty zones in Fig. 5, which represent topics for which existing experimental data have not yet been summarized or which have been the focus of only a few studies in the past. We discuss these knowledge gaps in Sect. 3.5. Finally, we use the outcome of our analysis to outline some key avenues for future research on the extent to which management practices can reinforce the water regulation function of soils.

3.1 Cropping systems and practices

Broadly speaking, published meta-analyses that have investigated the effects of cropping systems and practices (Fig. 5) 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 5 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, saturated hydraulic conductivity and aggregate

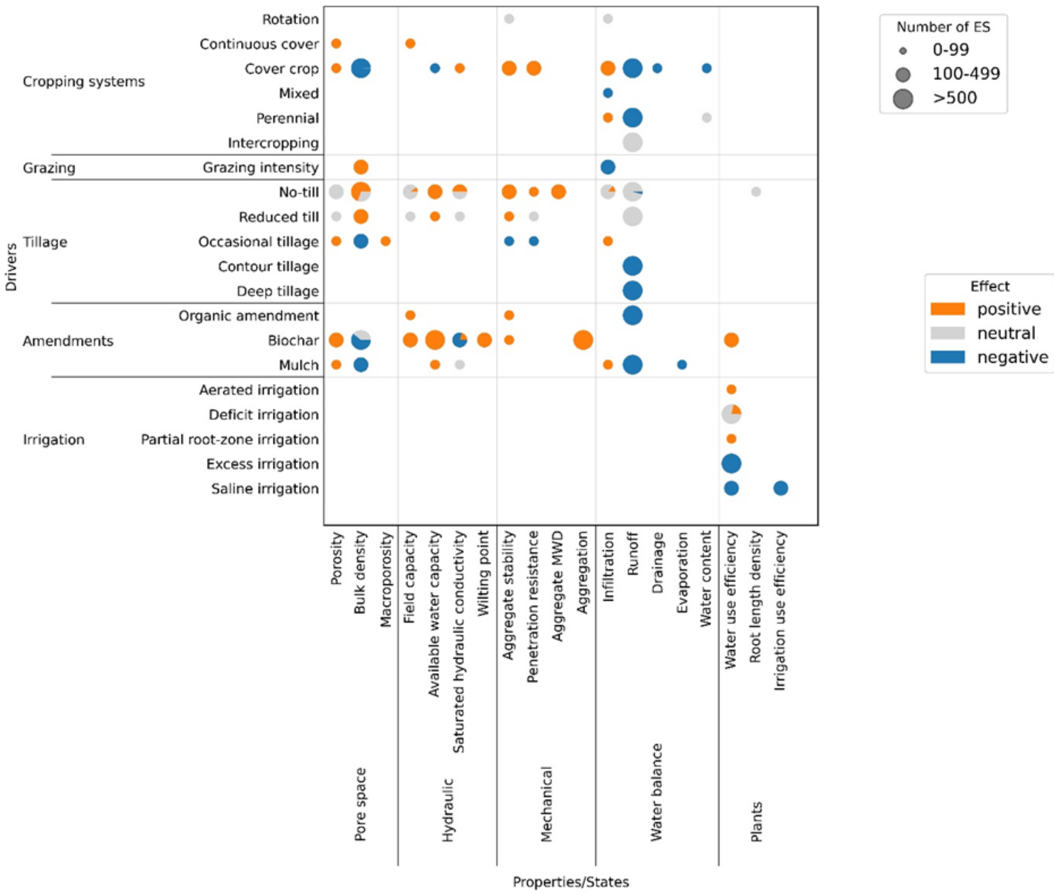

Figure 5. Effects of drivers (vertical axis) on target variables (horizontal axis) in the 36 selected meta-analyses. The colored pie charts represent the directions of the statistical effects in the different meta-analyses, while the size of the circle indicates the total number of effect sizes (ESs) reported. Note that this number has not been corrected for redundancy. Blank cells denote that no data were available for this target variable in any of the selected meta-analyses.

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 with leys and cover crops) promote increases in microbial biomass, activity and diversity (Muhammad et al., 2021; Venter et al., 2016; Shackelford et al., 2019; Kim et al., 2020; Jian et al., 2020) and increase soil organic matter contents in the long term (Poeplau and Don, 2015; McDaniel et al., 2014; McClelland et al., 2021; Shackelford et al., 2019; Bolinder et al., 2020; Aguilera et al., 2013; Bai et al., 2018; King and Blesh, 2018; Jian et al., 2020). This will both promote stable soil aggregation and reduce soil bulk density (Meurer et al., 2020a, b; Chenu et al., 2000). The abundance of soil meso- and macrofauna also increases under long-term cover cropping (Roarty et al., 2017; Reeleder et al., 2006) and perennial crops such as grass/-clover leys (Bertrand et al., 2015; Fraser et al., 1994; Jarvis et al., 2017). 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 (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 (Xiong et al., 2018; Liu et al., 2021; Lee et al., 2019; Basche and deLonge, 2019; Jian et al., 2020). 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 (Xiong et al., 2018; Liu et al., 2021; Basche and deLonge, 2019). These positive effects seem broadly similar regardless of climate (Xiong et al., 2018; Liu et al., 2021). As noted above, 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; Libohova et al., 2018; Minasny and McBratney, 2018a). One potential negative effect of cropping systems employing continuous living cover is that increased transpiration may reduce soil water contents (Shackelford et al., 2019) and decrease recharge to groundwater. Thus, for a combined dataset of 36 studies comprising both experimental and modeling studies, Meyer et al. (2020) found that cover crops reduced recharge by 27 mm yr^{-1} 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 as compared to bare inter-row strips.

3.1.1 Synergies and trade-offs

Meta-analyses have shown that cover crops mostly have either neutral or positive effects on main crop yields (Quemada et al., 2013; Tonitto et al., 2006; Valkama et al., 2015; Marcillo and Miguez, 2017; Angus et al., 2015). However, Shackelford et al. (2019) reported an average 7 % reduction in cash crop yields for systems employing nonlegume cover crops in dry Mediterranean climate conditions. Similarly, in a recent meta-analysis on cover crops grown in climates with less than 500 mm annual rainfall, Blanco-Canqui et al. (2022) found that cover crops decreased main crop yields in 38 % of cases, with no effects found in 56 % of cases and increased yields in 6 % of cases. Nonleguminous cover crops significantly reduce nitrate leaching and, to a lesser extent, N_2O emissions, although this is clearly not the case for legumes (Quemada et al., 2013; Muhammad et al., 2019; Tonitto et al., 2006; Valkama et al., 2015; Shackelford et al., 2019; Basche et al., 2014). Our literature search did not identify any meta-analyses on phosphorus or pesticide losses.

3.2 Tillage systems

The effects of tillage practices on soil properties and functions have been widely investigated (Fig. 5). The control treatment in meta-analyses is usually conventional tillage (CT), which involves both inversion plowing 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 plowed, or no-till (NT) systems in which the soil is left completely undisturbed, or both. 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 (Li et al., 2019, 2020a; Lee et al., 2019) due to continued traffic compaction of other field operations and the lack of mechanical loosening by cultivation (Hamza and Anderson, 2005). Peixoto et al. (2020) showed that these negative effects can be alleviated with occasional tillage.

Soil tillage indirectly affects soil structure through effects on soil macrofauna. In addition to the direct impacts of tillage implements on mortality, disruption of the soil also exposes soil macrofauna to increased risks of desiccation and predation. Consequently, meta-analyses show that total earthworm biomass and abundance increase as tillage intensity is reduced (Spurgeon et al., 2013; Bai et al., 2019; 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 favored by NT systems, as their permanent burrows are no longer destroyed by plowing, 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 (Spurgeon et al., 2013; Briones and Schmidt, 2017; Chan, 2001) and soil fauna in general (Graaff et al., 2019).

Reductions in the depth and intensity of tillage (i.e., from CT to RT to NT) strongly influence carbon cycling in the soil–crop system. Several meta-analyses show that soil organic carbon concentrations are larger under RT and NT systems in the uppermost soil layers (Lee et al., 2019; Bai et al., 2019), especially in fine-textured soils. 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) and the elimination of physical mixing and redistribution of C within the topsoil due to the absence of soil inversion by plowing (Meurer et al., 2020b). Meta-analyses have shown that the accumulation of SOM typically found in surface soil layers under RT and NT systems, which reflects the deposition and accumulation of plant residues, is paralleled by a greater microbial biomass (Li et al., 2020c; Lee et al., 2019; Spurgeon et al., 2013; Zuber and Villamil, 2016; Li et al., 2019; Chen et al., 2020; Li et al., 2020d) and increases in enzyme activities (Lee et al., 2019; Zuber and Villamil, 2016). The diversity of bacterial and sometimes also fungal communities tends to be greater in RT or NT (Graaff et al., 2019; Spurgeon et al., 2013; Li et al., 2020d), especially where these systems are combined with the retention of crop residues (Li et al., 2020d) Meta-analyses also show that aggregate stability is largest under NT systems, intermediate when occasional tillage is practiced (Peixoto et al., 2020) and smallest in CT systems (Bai et al., 2018). In their meta-analysis, Spurgeon et al. (2013) showed that improved aggregate stability under NT systems was positively correlated with increases in fungal biomass. NT also increases the mean size of aggregates produced in stability tests (Li et al., 2020a; Mondal et al., 2020). Several meta-analyses have demonstrated increases in field capacity and available water capacity under reduced and no-till systems (Li et al., 2019, 2020a; Mondal et al., 2020), presumably due to enhanced soil biological activity and increases in organic carbon content.

The impacts of conservation tillage practices on soil biological agents and processes give rise to significant indirect effects on physical properties and hydrological processes. Saturated hydraulic conductivity and surface infiltration rates often increase under conservation tillage compared with CT, especially for NT systems (Basche and deLonge, 2019; Li et al., 2019; Mondal et al., 2020; Li et al., 2020a). This suggests that the effects of the enhanced bio-porosity 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 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. In principle, better-developed soil macropore systems and improvements in aggregate stability and infiltration capacity should promote a more favorable crop water balance, with reductions in surface runoff. Figure 5 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. (2015) found that RT and NT 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. (2018) found that contour tillage and deep tillage both reduced surface runoff.

3.2.1 Synergies and trade-offs

Adoption of no-till and reduced tillage systems involve several trade-offs, particularly concerning water quality, greenhouse gas (GHG) emissions and crop yields. NT systems tend to give smaller yields for many crops compared with conventional tillage (Mangalassery et al., 2015; Sun et al., 2020b; Pittelkow et al., 2015b). 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. Pittelkow et al. (2015a) identified several reasons for variations in the yield response to no-till practices. 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. Pittelkow et al. (2015a) and Sun et al. (2020a) also show that climate is 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 increased crop yields compared with NT in dry regions and in soils with limited water retention capacity and availability, presumably by alleviating soil compaction and improving rooting.

With respect to water quality, Daryanto et al. (2017a) found 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 four compounds. For loads, no significant difference was detected 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. (2018), 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 in 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. We did not find any meta-analyses on the effects of tillage systems on pesticide leaching in our literature search. Leaching is the outcome of several interacting processes involving many complex and poorly understood processes (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 soil organic carbon (SOC), since these will affect water flow velocities, degradation rates and the strength of adsorption in soil. Several studies suggest that the better-preserved macropore networks established under RT and NT systems may enhance leaching by preferential flow (Jarvis, 2007; Larsbo et al., 2009; Alletto et al., 2010). 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 practices on N_2O emissions, with observed increases in humid climates compensated for 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_2O emissions under conservation tillage, with the largest effects in warmer and wetter climates and in finer-textured soils. Shakoor et al. (2021) found significant increases of emissions of CO_2, N_2O and CH_4 of 7 %, 12 % and 21 % respectively under NT compared with CT. From the perspective of climate change mitigation, Guenet et al. (2020) concluded that increased greenhouse gas emissions under NT outweighed any minor gains in soil C stocks.

3.3 Amendments

3.3.1 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 pyrolysis. Apart from its potential for long-term soil carbon sequestration, it can also have beneficial effects on nutrient availability and soil physical properties (Joseph et al., 2021). The quantitative analysis of the effects of biochar on physical and hydraulic properties shown in Fig. 5 is based on effect ratios presented in five meta-analyses (Rabbi et al., 2021; Edeh et al., 2020; Omondi et al., 2016; Gao et al., 2020; Islam et al., 2021). Our review draws on findings presented in two additional reviews that employed different statistical methodologies (Razzaghi et al., 2020; Kroeger et al., 2020). Rabbi et al. (2021) only presented data for various subcategories (e.g., for different types of biochar) and not for the overall effects of biochar addition. Taken altogether, these seven studies present results of analyses for different soil types, textural classes and experimental conditions (i.e., field or laboratory/greenhouse study), as well as for biochars of different properties and applied at different rates. These analyses show that biochar has several positive effects on soil hydraulic properties but that these effects are dependent on all of the above-mentioned variables.

Decreases in bulk density and increases in porosity are generally reported after biochar addition (Edeh et al., 2020; Omondi et al., 2016). 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 will increase. Biochar will also influence these variables indirectly through its effects on aggregation (Pituello et al., 2018). 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 Islam et al. (2021) included studies that reported soil aggregate stability as a percentage of water-stable aggregates (WSAs), 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 and that these effects increased with the time between biochar application and measurements (Islam et al., 2021).

Figure 5 suggests that biochar addition generally increases the plant-available water content (θ_{paw}). These meta-analyses show that although the water contents at field capacity (θ_{fc}; pressure potentials in the range between -0.033 and -0.01 MPa) and wilting point (θ_{pwp}) both tend to increase following biochar amendment, the effects on θ_{fc} appear to be larger (Fig. 5). Pore sizes in biochars range over at least 5 orders of magnitude, from the sub-nanometer scale to pore diameters of the order of tens of micrometers 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 increase the wilting point water content 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 µm in diameter) to contribute to θ_{paw}. Additionally, inter-particle pores in biochar may also contribute to θ_{paw} depending on the size distribution and shapes of the biochar particles. 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 of biochar 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 the smaller pores that can retain water at the pressure potentials corresponding to field capacity (Rabbi et al., 2021; Edeh et al., 2020; Omondi et al., 2016). Moreover, fine-textured soils retain more water at θ_{fc} so that the relative changes induced by biochar may be smaller (Edeh et al., 2020).

All the meta-analyses included data on the effects of biochar production parameters (e.g., feedstock and pyrolysis temperature) and the chemical and physical properties of biochar. Generally, the influence of these parameters on the effects of biochar addition was 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., 2016).

One meta-analysis reported an increase in saturated hydraulic conductivity following biochar addition (Omondi et al., 2016), while two others reported negative effects (Fig. 5). Saturated hydraulic conductivity is a function of pore network properties, including connectivity of the macropores and the presence of pore bottlenecks (Koestel et al., 2018). A few studies have quantified the effects of biochar addition on the connectivity of macropore networks using X-ray tomography (Yan et al., 2021; Yu and Lu, 2019). 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 is not consistent.

The effects of biochar on the studied variables were in many cases larger for higher application rates. Often, laboratory studies used much larger application rates ($>50\,\mathrm{t\,ha^{-1}}$) than field studies and also reported larger effects. 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 historical biochar sites. The meta-analyses show large variations in effects for all the included variables, which suggests that future work should also be directed towards finding biochars with specific properties (e.g., surface area and particle size) designed to improve soil physical properties under specific soil and climate conditions while maintaining or improving nutrient availability.

3.3.2 Other organic amendments, residue retention and mulching

Figure 5 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 has 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. Xiong et al. (2018) found that application of soil amendments reduced both surface runoff and soil erosion. Gravuer et al. (2019) analyzed 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 to add (or retain) 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 amendments may have several beneficial effects on soil quality and the environment and is therefore one important practice in conservation agriculture. Mulching is typically carried out to limit soil evaporation and 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 (Fig. 5). Three meta-analyses analyzed the effects of mulching on surface runoff, one for agricultural land Xiong et al. (2018), one for annual crops (Ranaivoson et al., 2017) and one focusing only on tree crops (Liu et al., 2021). They all showed reduced surface runoff. The study for annual 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, which also includes the comparison between residue retention and removal in no-till systems. Residue retention led to a decrease in bulk density, an increase in total porosity and an increase in plant-available water, whereas 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.

Overall, organic amendments have potentially beneficial effects for several soil properties relevant for water regulation. Although this is not a new observation, techniques such as mulching or biochar application are still rather little applied. Residue retention is more common in the EU, but worldwide residues are often still burnt on the field or collected for other uses. The limited availability of the organic material at the right place at the right time and for an acceptable price is most probably one of the major bottlenecks for a widespread application of these amendments, especially in the case of biochar. Future research in this field should therefore urgently tackle the socio-economic challenges related to the availability of organic amendments that prevent their widespread use.

3.4 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 (Lu et al., 2019; Yu et al., 2020; Cheng et al., 2021a; Adu et al., 2018; 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 (Fig. 5), 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 (Fig. 5) depend on crop type, irrigation methods, climates and soil type.

3.5 Knowledge gaps

Figure 5 shows that only one meta-analysis has studied the effects of management on crop root system characteristics. This is most probably because root system characterization is tedious, time-consuming and too invasive for long-term field trials. Nevertheless, the soil–root interface is a crucial environment mediating the flow of water in the soil–plant–atmosphere system. It can be expected that many soil management practices influence root penetration and rooting depths, thereby strongly influencing potential rates of water uptake by plants during droughts. At present, we can only make inferences about the effects of soil management on crop transpiration, either from other terms in the soil water balance or from the use of penetration resistance as a proxy.

We also showed that although several recent meta-analyses have investigated the impacts of different irrigation scheduling strategies on water use efficiency and crop yields, none has so far summarized the effects of irrigation on soil physical properties. Nevertheless, the type of irrigation technique (e.g., surface, sprinkler or drip irrigation) and the quality of water used are known to strongly affect soil structure and hydraulic properties (Sun et al., 2018; Leuther et al., 2019; Drewry et al., 2020), which should impact the water regulation functions of soil. A quantitative summary of existing experimental information would provide critical support to policies and practices for effective adaptation of farming systems to future climates with more frequent and severe summer droughts.

We would also like to highlight some additional knowledge gaps that are not revealed in Fig. 5. Firstly, with some exceptions (i.e., tillage practices and residue management), most long-term field experiments only have simple designs that neglect some potentially interesting combinations of treatments (e.g., the interactions between soil and crop management and irrigation systems). Secondly, some key target variables are rarely measured and so have not yet been the subject of meta-analysis. For example, most long-term field trials on the effects of soil and crop management practices on hydrological functioning have measured proxy variables for soil structure, such as infiltration or soil hydraulic properties (water retention, hydraulic conductivity at and near saturation). No meta-analyses have been performed yet for metrics quantifying various aspects of soil structure per se (Rabot et al., 2018), even though the application of X-ray imaging techniques to quantify soil structure is becoming increasingly common. As a result, the number of X-ray studies published is rapidly increasing, so it should soon be possible to carry out such an analysis.

4 Conclusions and outlook

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. Across Europe, climatic extremes (i.e., droughts and intense rains) will become more frequent and more severe. Specifically, effective adaptation to climate change requires soils with a well-developed and stable structure with a large infiltration capacity and an ability to sustain water supply to plants during extended dry periods. This synthesis has revealed a considerable degree of consensus concerning the effects of soil and crop management practices on key soil properties relevant for these hydrological functions.

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. One potentially negative consequence of management practices that maintain continuous living cover is a reduction in soil water storage and groundwater recharge. This may be problematic in dry climates, where there is some evidence to suggest that yields of the main crop may be 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.

The amelioration of soil structure that occurs under reduced (RT) and no-till (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 inconclusive. Furthermore, 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. Greenhouse gas emissions are also 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.

Our extensive synthesis of the existing literature has also identified several important knowledge gaps, particularly related to the effects of management practices on soil structure, root growth and transpiration and on combinations of practices. 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.

To address these limitations, we recommend that future research should focus on the following:

1. monitoring transpiration (e.g., by sap flow) and crop root development in existing field trials and the development of techniques to do this in a minimally invasive way for the entire soil root zone,

2. monitoring of soil structure and hydraulic properties in field trials over the entire soil profile,

3. application of soil–crop models making use of measured hydraulic properties and climate model projections to evaluate and predict the impacts of alternative soil and crop management practices on water balance and crop yields under climate change,

4. introduction of irrigation and drought treatments at existing long-term field trials to investigate the consequences for water regulation functions under climate change.

Appendix A: Redundancy analysis

Note that for this analysis, the studies of Li et al. (2019) and Li et al. (2020b) were considered as one, as they both rely on the same database but analyze different variables. We first identified the studies shared between multiple meta-analyses and computed the percentage of shared studies per meta-analysis. Figure A1 shows the percentage of shared studies (number of shared studies divided by number of studies in the meta-analysis in the row times 100). Figure A2 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, Fig. A2 also shows the number of primary studies included in each meta-analysis. For example, Jian et al. (2020), Li et al. (2020) and Mondal et al. (2020) considered more than 200 primary studies in their meta-analyses. Finally, Fig. A3 shows for each meta-analysis the percentage of its primary studies that are shared with another meta-analysis. For example, the studies by Omondi et al. (2016) and Rabbi et al. (2021) share a large proportion of primary studies. Figure A3 also shows that nearly all the primary studies included in these two meta-analyses are shared with another meta-analysis.

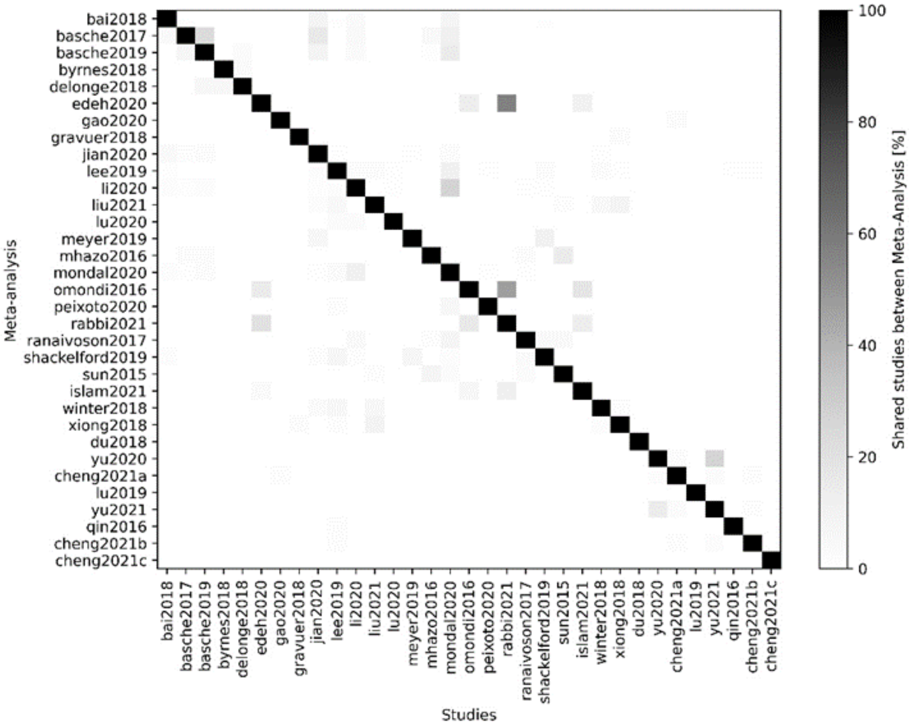

Figure A1. Redundancy matrix showing the percentage of shared studies among meta-analyses. The percentage refers to the number of shared studies divided by the total number of studies in the meta-analysis in the row. Note that this matrix is not symmetrical because the percentage is computed for the 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.

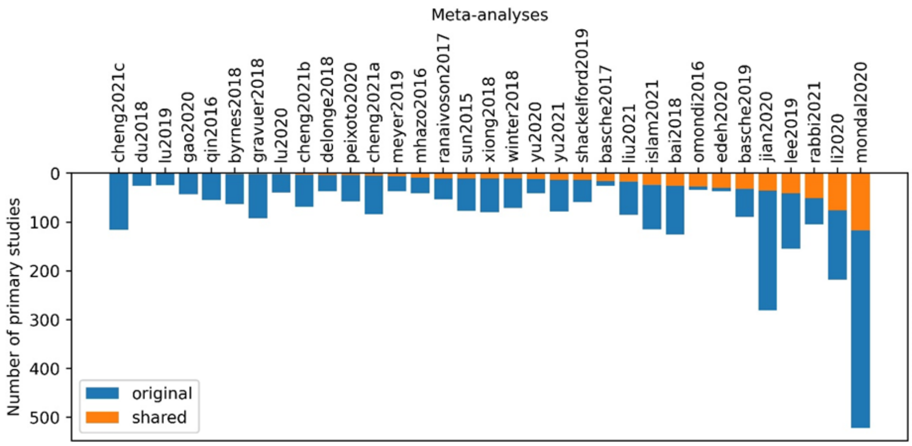

Figure A2. Histogram showing the number of primary studies per meta-analysis. The studies shared by at least one other meta-analysis are displayed in light green (shared), while the studies found only in this meta-analysis are shown in dark green (original).

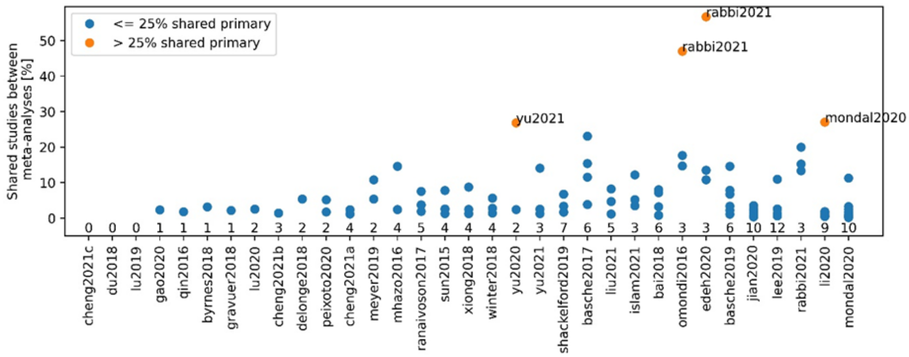

Figure A3. Redundancy among the selected meta-analyses (horizontal axis). Dots represent the percentage of shared primary studies between two meta-analyses. When this percentage is above 25 %, the dots are shown in red, and the name of the meta-analysis is displayed. For instance, Li et al. (2020c) share 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-analyses are sorted according to the number of shared primary studies they have (same order as Fig. A2).

Appendix B: Meta-analyses on soil and crop management and water regulation in the EU

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Code and data availability. The dataset collected during this study as well as the processing codes to reproduce the figures of this manuscript is available at https://doi.org/10.5281/zenodo.7470450 (Blanchy et al., 2022). The Authors of the manuscript are the authors of the repository.

Author contributions. All co-authors conceptualized the paper. GuB, GiB, and NJ conducted the analysis and collected the data. Writing of the original draft: GuB, NJ, ML, KM, and SG wrote the original draft, while all co-authors participated in the writing, review, and editing of the paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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