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Soil and crop management practices and the water regulation functions of soils: a 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 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 is enhanced under reduced tillage intensity, which should improve soil structure, 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.

1 Introduction

The occurrence of extreme weather events, such as high temperatures, summer droughts, waterlogging and flooding, will most probably increase in many parts of Europe as a consequence of on-going climate change (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 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, 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 (figure 1). In turn, soil structure strongly affects all life in soil as well as 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. 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 FAO (2010) as "… *agriculture that sustainably increases productivity, enhances resilience, reduces greenhouse gases, and enhances achievement of national food security and development goals*".

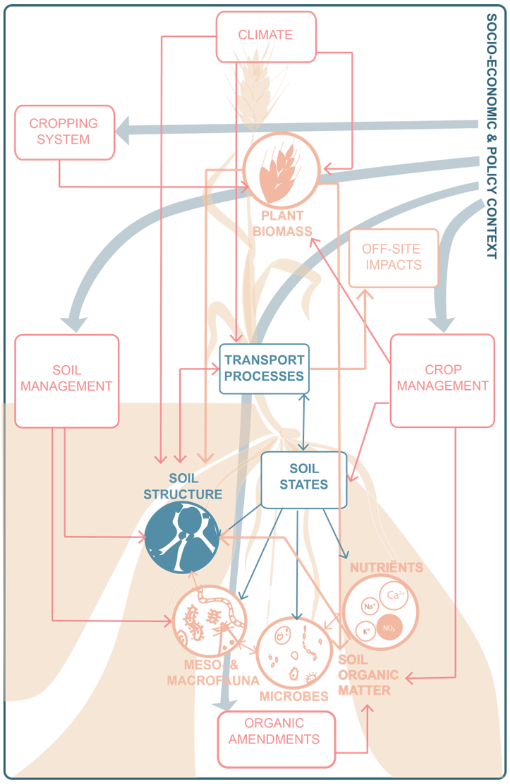

Figure 1. Schematic diagram of drivers, agents and processes governing the dynamics of soil structure and its effects on the soil-plant system.

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,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. (2020) 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.

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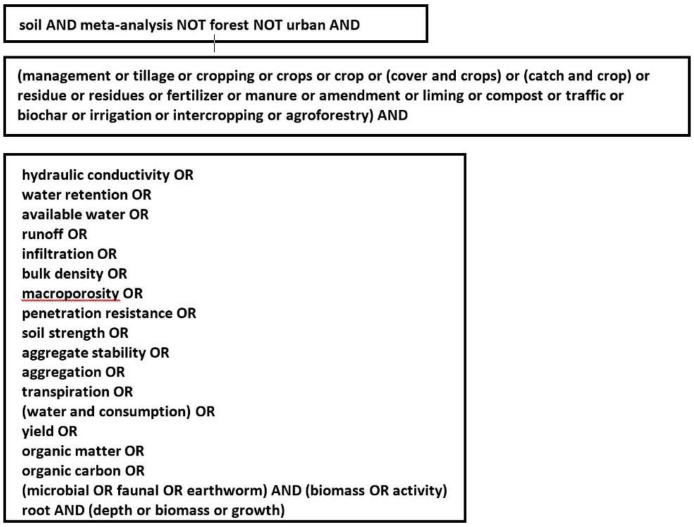
Tamburini et al. (2020) concluded that diversification practices most often resulted in a ‘win-win’ situation for ecosystem services including crop yields, but that the often large variability in responses and the occurrence of trade-offs highlighted the need to analyze the context-dependency of outcomes, something which was only possible to do to a limited extent with their broad-brush treatment. These 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,b; Bolinder et al., 2020) 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. (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. This evaluation highlights where consensus has been established and identifies remaining knowledge gaps. 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.

2 Materials and Methods

2.1 Literature search



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.

The text string shown in Figure 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 effects ratios (Appendix 2). 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*”).

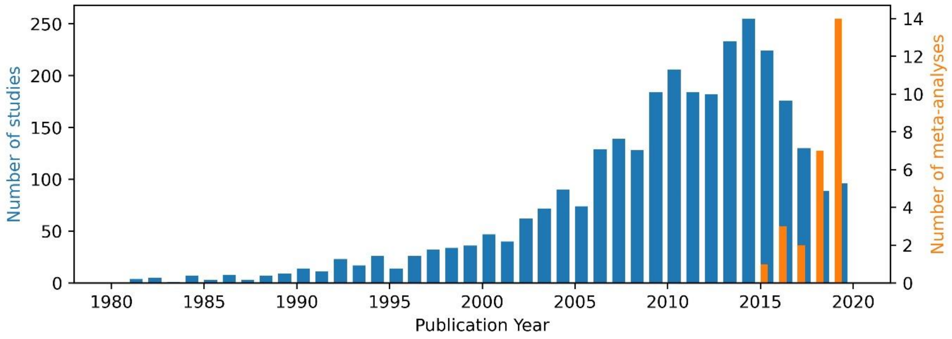


Figure 3. Number of primary studies included in the 36 selected meta-analyses published per year and the publication year of these meta-analyses.

The target variables (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, 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). Likewise, the management practices were also grouped into five 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, the 34 meta-analyses reported 104 effects ratios comparing the impacts of a management practice to a control treatment for a particular response variable. The effects of these treatments on the target variables (either positive, negative or neutral i.e. non-significant) were read from tables and figures in each of the 34 meta-analyses.

2.2 Quality assessment

FWe 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 the important issue of publication bias (Philibert et al., 2012). The authors of these 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 with 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. Two studies detected evidence of publication bias (e.g. Basche and deLonge, 2019; Shackleford et al., 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 mostly robust results for the impacts of management practices on infiltration, especially for no-tillage and cover crops.

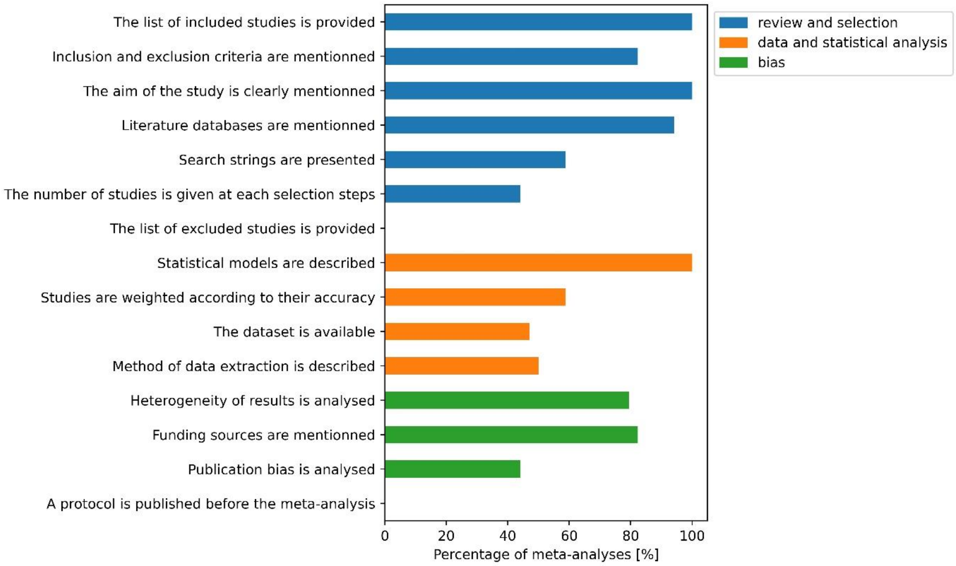


Figure 4. Proportion of the quality criteria defined by Bellouin et al. (2019a) that are met by the selected meta-analyses in this study.

2.3 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. (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 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. The results of the redundancy analysis are presented in the Appendix 1 (Figures A1-A3) as well as in the notebook at https://github.com/climasoma/review-of-meta-

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analyses/blob/main/notebooks/redundancy.ipynb. The main outcome of this analysis is that redundancy is only an important factor for a few meta-analyses on biochar that were published almost simultaneously (e.g. Edeh, et al., 2020; Rabbi, et al., 2021).

3 Results and discussion

3.1 Knowledge gaps

Figure 5 summarizes the statistical relationships found between the drivers and target variables in the selected meta-analyses. Gaps in the scatter plots shown in figure 5 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, none have been published specifically on the effects of management practices on water supply to crops. Such information should be critical to support policies and practices for effective adaptation of farming systems 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 5 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.

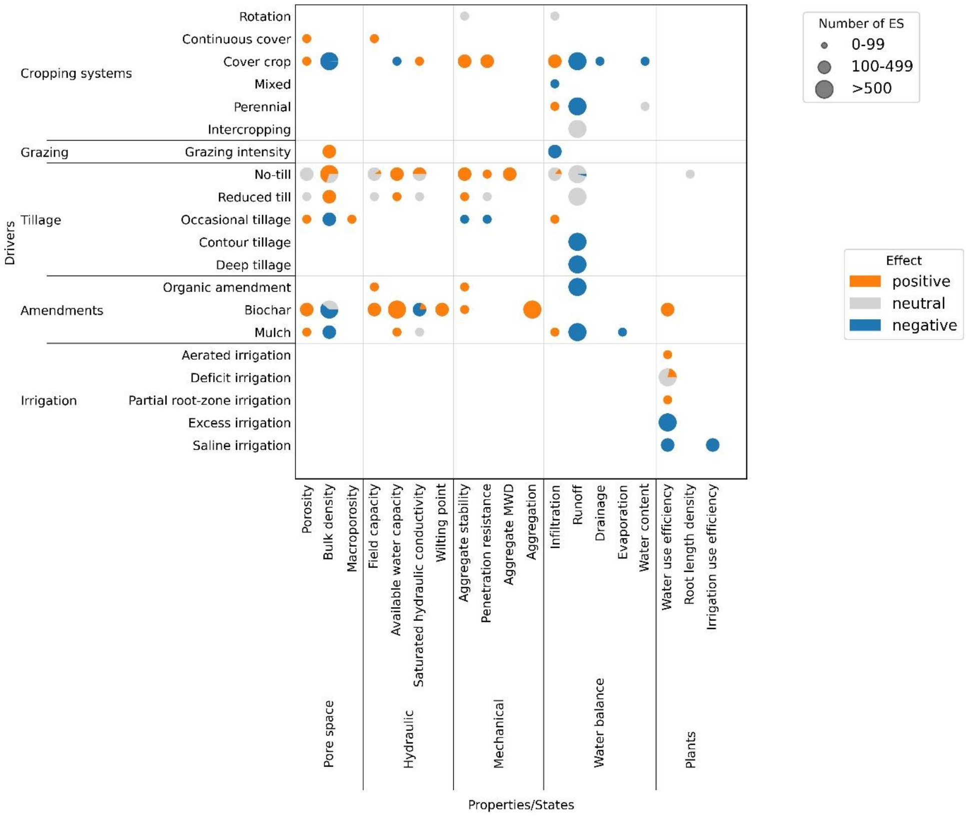

Figure 5. Effects of drivers (vertical axis) on target variables (horizontal axis) in the 36 selected meta-analyses. The coloured pie charts represent the directions of the statistical effects in the different meta-analyses, while the size of the circle indicates the total number of effects sizes (ES)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

Some additional potential knowledge gaps concerning the effects of soil management on water regulation functions are not revealed by inspection of figure 5, 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.

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3.2 Cropping systems and practices

Broadly speaking, published meta-analyses that have investigated the effects of cropping systems and practices (figure 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 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, cover crops) promote increases in microbial biomass, activity and diversity (Venter et al., 2016; Shackleford et al., 2019; Jian et al., 2020; Kim et al., 2020; Muhammad et al., 2021) and increase soil organic matter contents in the long-term (Aguilera et al., 2013; McDaniel et al., 2014; Poeplau and Don, 2015; King and Blesh, 2018; Bai et al., 2019; Shackleford et al., 2019; Bolinder et al., 2020; Jian et al., 2020; McClelland et al., 2021). This will both promote stable soil aggregation and reduce soil bulk density (Chenu et al., 2000; Meurer et al., 2020a,b). The abundance of soil meso- and macro-fauna 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; Bertrand et al., 2015; 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 (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 (Xiong et al., 2018; Basche and deLonge, 2019; Lee et al., 2019; Jian et al., 2020; Liu et al., 2021). 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; Basche and deLonge, 2019; Liu et al., 2021). These positive effects seem broadly similar regardless of climate (Xiong et al., 2018; Liu et al., 2021).

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 (deLonge and Basche, 2018; Basche and deLonge, 2019) 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 negative effect is that by increasing transpiration, systems employing “continuous living cover” may reduce soil water content (Shackleford 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, for example 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, 2018a,b; Libohova et al., 2018).

With respect to potential synergies and trade-offs, studies have shown that cover crops mostly have either neutral or positive effects on main crop yields (Tonitto et al., 2006; Quemada et al., 2013; Valkama et al., 2015; Angus et al., 2015; Marcillo and Miguez, 2017). However, Shackleford et al. (2019) reported an average 7% reduction in cash crop yields for systems employing non-legume 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. Non-leguminous cover crops significantly reduce nitrate leaching and, to a lesser extent, N_2O emissions, although this is clearly not the case for legumes (Tonitto et al., 2006; Quemada et al., 2013; Basche et al., 2014; Valkama et al., 2015; Muhammad et al., 2019;

Shackleford et al., 2019). Our literature search did not identify any meta-analyses on phosphorus or pesticide losses.

3.3 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 (figure 5). 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 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 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 (e.g. Bai et al., 2018; Lee et al., 2019) 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) and 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., 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 (e.g. Spurgeon et al., 2013; Zuber and Villamil, 2016; Li et al. 2018; Lee et al. 2019; Li et al. 2020b,c; Chen et al. 2020) and increases in enzyme activities (Zuber and Villamil, 2016; Lee et al., 2019). The diversity of bacterial and sometimes also fungal communities tends to be greater in RT or NT (Spurgeon et al., 2013; de Graaff et al., 2019; Li et al 2020b), especially where these systems are combined with the retention of crop residues (Li et al., 2020c).

In addition to focusing on organic carbon concentrations in topsoil, differences in SOC stocks under conservation tillage systems in complete crop root zones and soil profiles are also of interest, not least from the point of view of climate change mitigation. Based on a meta-analysis of studies with measurements made to at least 40 cm depth, Luo et al. (2010) concluded that NT did not increase soil carbon stocks. This is because although SOC contents are usually larger under NT than CT systems in the uppermost soil layers, they can be

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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 apparent contrast, Mangalassery et al. (2015) concluded that NT systems result in a net sequestration of carbon, regardless of the depth of soil considered. Sun et al. (2020) demonstrated significant effects of climate on the changes in organic carbon stocks observed 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 just 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 Gonzalez-Sanchez 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 can be explained by a decrease in carbon inputs to soil resulting from poorer crop growth (Mangalassery et al., 2015; Pittelkow et al., 2015), which compensates for reductions in carbon mineralization rates (Ogle et al., 2012; Virto 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 (Spurgeon et al., 2013; Briones and Schmidt 2017; Bai et al. 2018), 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 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 (Chan, 2001; Spurgeon et al., 2013; Briones and Schmidt 2017) and soil fauna in general (de 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., 2019; Li et al., 2020a) due to 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 increase under conservation tillage compared with CT, especially for NT systems (Li et al., 2019; Basche and deLonge, 2019; Li et al., 2020a; Mondal et al., 2020). 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, is 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. A lack of soil disturbance in NT systems 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; Mondal et al., 2020; Li et al., 2020a), 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 would appear to be relatively small.

In principle, better-developed soil macropore systems and improvements in aggregate stability should promote a more favorable crop water balance, with increases in infiltration and 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 (Mhazo et al., 2016; Xiong et al., 2018) 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.

Adoption of no-till and reduced tillage 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 (Mangalassery et al., 2015, Pittelkow et al., 2015, Sun et al., 2020). This may explain why no-till systems are still seldom adopted in Europe (Mangalassery et al., 2015; Bai et al. 2018), although reduced tillage (RT) is being increasingly adopted worldwide. In their comprehensive meta-analysis, Pittlekow et al. (2015) 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, Pittlekow 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 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 4 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 SOC, since

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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 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 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.

3.4 Amendments

3.4.1 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 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).

The quantitative analysis of the effects of biochar on physical and hydraulic properties shown in figure 5 is based on effects ratios presented in five meta-analyses (Omondi et al., 2016; Edeh et al., 2020; Gao et al., 2020; Rabbi et al., 2021; Ul Islam et al., 2021). Our review also draws on findings presented in two additional reviews that employed different statistical methodologies (Kroeger et al., 2020; Razzaghi et al., 2020). Rabbi et al. (2021) only presented data for various sub-categories (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,

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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 (Omondi et al., 2016; Edeh, et al., 2020). 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).

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 (figure 5). 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 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 have the potential to 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}. 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 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 (Omondi et al., 2016; Edeh et al., 2020; Rabbi et al., 2021). 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, pyrolysis temperature) and the chemical and physical properties of biochar. Generally, the influence of these parameters

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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 (e.g. Cheng et al., 2008; Hardy et al., 2017).

One meta-analysis reported an increase in saturated hydraulic conductivity following biochar addition (Omondi et al., 2016), while two others reported negative effects (figure 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 (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 is 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 (Ul Islam et al., 2021).

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 CO_2 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 climates that exist. 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.

3.4.2 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. 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 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, 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.

3.5 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 (Qin et al., 2016; Adu et al., 2018; Lu et al., 2019; Yu et al., 2020; Cheng et al., 2021a,b). 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., 2021a) 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 suppling 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 (figure 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. (2021c) showed how the decreases in water productivity, irrigation use efficiency and crop yields as a result of the use of salty irrigation water (figure 5) 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.

4 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 management practices on 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

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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, where there is 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.

There is little evidence from meta-analyses to support the idea that reductions in tillage intensity improve crop water supply. 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 inconclusive. 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.

Appendices

Appendix 1 Redundancy analysis

Note that for this analysis, the studies of Li et al. (2019) and Li et al. (2020) 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). 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, 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, 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. A3 also shows that nearly all the primary studies included in these two meta-analyses are shared with another meta-analysis.

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.

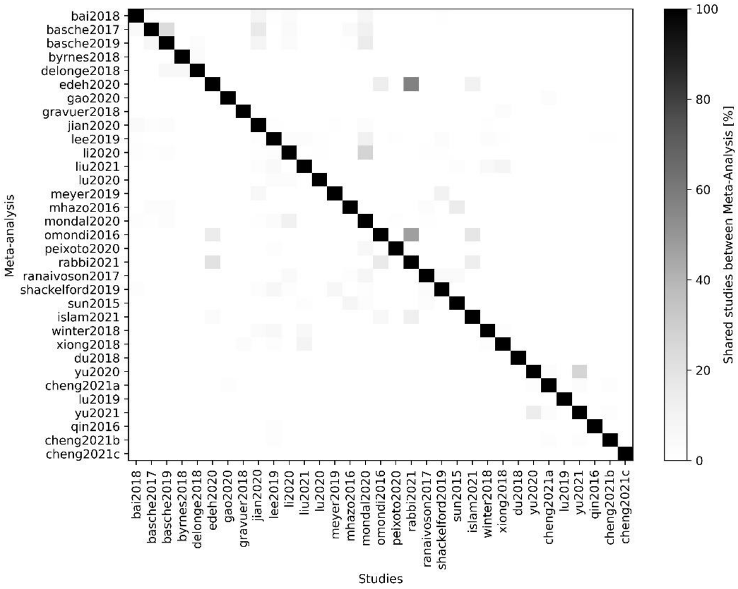

Figure A1: Redundancy matrix showing the percentage of shared studies among meta-analyses.

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).

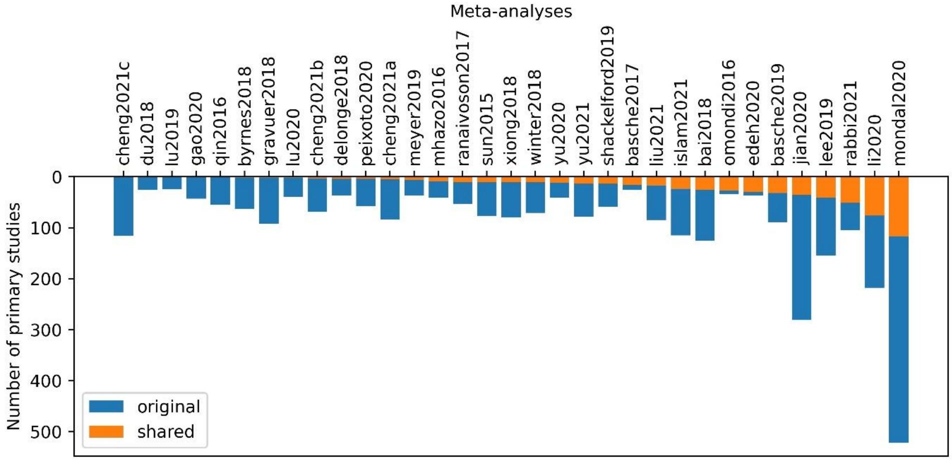

Figure A2: Histogram showing the number of studies per meta-analysis.

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. (2020) 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 A2).

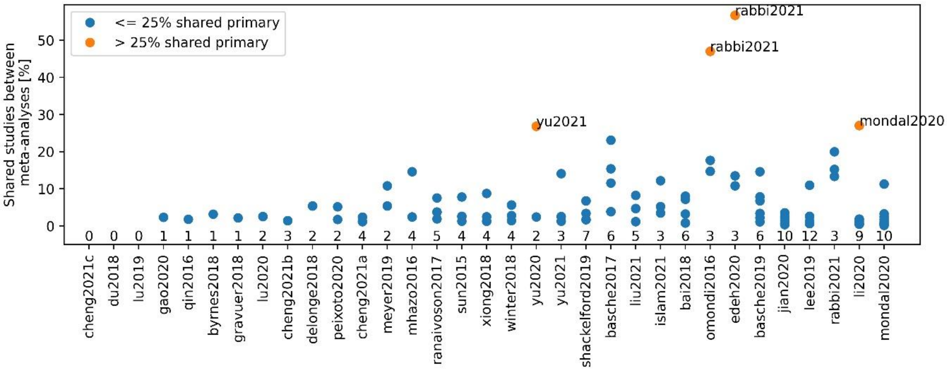

Figure A3: Redundancy among the selected meta-analyses (horizontal axis). Dots represent the percentage of shared primary studies between two meta-analyses.

Appendix 2 Meta-analyses on soil/crop management and water regulation in the EU

Bai, Z., Caspari, T., Gonzalez, M., Batjes, N., Mäder, P., Bünemann, E., de Goede, R., Brussaard, L., Xu, M., Ferreira, C., Reintam, E., Fan, H., Mihelič, R., Glavan, M., Tóth, Z. 2018. Effects of agricultural management practices on soil quality: a review of long-term experiments for Europe and China. Agriculture, Ecosystems and Environment, 265, 1-7.

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Code availability

Code is available at https://github.com/climasoma/review-of-meta-analyses

Data availability

Data is available at https://github.com/climasoma/review-of-meta-analyses

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