

Review

A Review of Crop Husbandry and Soil Management Practices Using Meta-Analysis Studies: Towards Soil-Improving Cropping Systems

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Abstract: Coherent improvements in crop varieties and crop husbandry and soil management practices are needed to increase global crop production in a sustainable manner. However, these practices are often discussed separately, and as a result there is little overview. Here, we present a database and synthesis of 154 meta-analysis studies related to ten main crop husbandry and soil management practices, including crop type and rotations, tillage, drainage, nutrient management, irrigation and fertigation, weed management, pest management, crop residue management, mechanization and technology, and landscape management. Most meta-analysis studies were related to tillage (55), followed by crop type and rotations (32), nutrient management (25), crop residue management (19), and irrigation and fertigation (18). Few studies were related to landscape management (6) and mechanization and technology (2). In terms of outcome, studies focused on crop yield and quality (81), soil quality (73), and environmental impacts (56), and little on economic effects (7) or resource use efficiency (24). Reported effects of alternative practices, relative to conventional practice, were positive in general. Effect sizes were relatively large for environmental effects (nutrient leaching, greenhouse gas emissions), and small for soil quality (except for soil life) and crop yield. Together, meta-analysis studies indicate that there is large scope for increasing cropland productivity and minimizing environmental impacts. A roadmap is provided for integration and optimization of all ten practices, and recommendations are formulated to address the gaps in meta-analysis studies.

Keywords: crop residue; crop rotation; crop yield; environmental effects; irrigation; nutrient management; resource use; soil-improving cropping systems; soil quality; tillage



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1. Introduction

Global yields of main crops (wheat, rice, maize, and soybean) have increased by an average 1 to 2% per year during the last decades [1,2], in response to the increasing global food and feed demands, and facilitated through technological improvements. Forecasts suggest that mean crop yields per ha of cropland have to increase by as much as 2.4% per year to be able to meet the food and feed demands by the human population in 2050, also because further expansion of global cropland area and/or increased frequency of harvesting are not feasible [3,4]. The slow-moving mean increase in global crop yields during recent decades are in part related to areas where crop yields have been stagnating and to areas where crop yields have not increased at all or have fallen. Recent analyses suggest that crop yields are not increasing on 25 to 40% of the harvested global cropland area [1]. Yield increases of wheat, maize, and rice tend to be lowest in low-income countries because of lack of resources and poor crop husbandry practices. In high-income countries, yield increases may be less than average when actual yields approach attainable crop yields, suggesting that yields reach biophysical limits [5,6]. Crop yields may also stagnate in some countries because of climate change and environmental regulations [7–9] and soil degradation [10–12].

The yield increases per unit of surface area during recent decades have mainly been the result of improved germplasm and improved crop husbandry and soil management practices, including inputs of fertilizers, irrigation, and pesticides [13]. Availability of high-yielding cultivars, fertilizers, irrigation water, and pesticides are commonly considered to be the dominant yield-controlling factors, next to climate and soil quality. However, the importance of precise timing and careful execution of the various crop husbandry practices in the proper order should not be neglected [13]. The crop husbandry and soil management practices together determine how far actual crop yields deviate from attainable crop yields and from potential crop yields [14]. Attainable crop yields, defined as the best yield achieved by the best farms through skillful use of the best available technology [14], are on average 70 to 80% of the potential yield. Potential crop yields are commonly defined as the yields obtained when cultivars adapted to the local environmental conditions are grown with minimal stress, achieved with best management practices [11,15,16]. Actual yields on farmers' fields range from 30 to 100% of attainable yields, depending on region [1].

Crop husbandry and soil management practices also influence the environmental sustainability of crop production systems, especially in cases where the pressures to increase crop yields are high. Concerns have arisen about intensive crop production systems with poor crop husbandry and soil management practices, as these pollute groundwater and surface waters with nitrogen (N), phosphorus (P) and pesticides, and emit greenhouse gases and ammonia (NH₃) into the atmosphere [15–17]. There are also concerns about soil degradation through processes such as erosion, salinization, compaction, and declines of soil organic matter content and soil biodiversity [10]. The United Nations (UN) Sustainable Development Goals (SDGs) address essentially all of these concerns and indirectly guide the actions of nations in the pursuit of a more sustainable world. Of the 17 SDGs, at least five have a direct relation with cropping systems and soils, while others have a more indirect relation [18]. SDG-2 aims to 'end hunger, achieve food and nutrition security, and promote sustainable agriculture' and is key to the success of the SDG agenda [19].

While there are several spatially explicit assessments of changes in crop yields over time (e.g., [2,20]), there are no spatially explicit, integrated assessments of the sustainability of crop husbandry and soil management practices. The main reason for this lack of assessments is the diversity of crop husbandry and soil management practices, and the lack of methods and procedures for making such integrated assessments. Wezel et al. [21] analyzed 15 agroecological cropping practices qualitatively in terms of possible advantages and drawbacks, for temperate areas. Others have reviewed the impacts of one or a few specific crop husbandry practices (e.g., [22–24]), often on the basis of a meta-analysis of published studies. There is as yet no coherent overview and comparison of the effects of all main crop husbandry and soil management practices.

The aim of this study was to provide a review of crop husbandry and soil management practices on the basis of meta-analysis studies. Meta-analysis papers commonly analyze and synthesize many experimental studies related to topical research questions and/or ambiguous research findings. The term 'meta-analysis' was first used in 1976 and referred to 'the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings' [25,26]. Most meta-analysis studies related to crop husbandry and soil management practices date from the last 10 to 20 years, and the cumulative number has increased exponentially (Figure 1).

Thus, our main hypothesis is that meta-analysis studies summarize and synthesize vast amounts of research results, and unravel underlying mechanisms of variations, and thereby provide overview. By reviewing and synthesizing meta-analysis studies related to several crop husbandry and soil management practices, we aimed to (i) summarize the main impacts of these crop husbandry and soil management practices, (ii) identify the most topical research areas, and (iii) suggest guidelines for 'sustainable cropping systems'. The crop husbandry and soil management practices examined were assessed in terms of (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency,

(e) environmental effects, and (f) human health impacts. However, none of the reviewed studies addressed human health impacts; as a consequence, this aspect is not reported here.

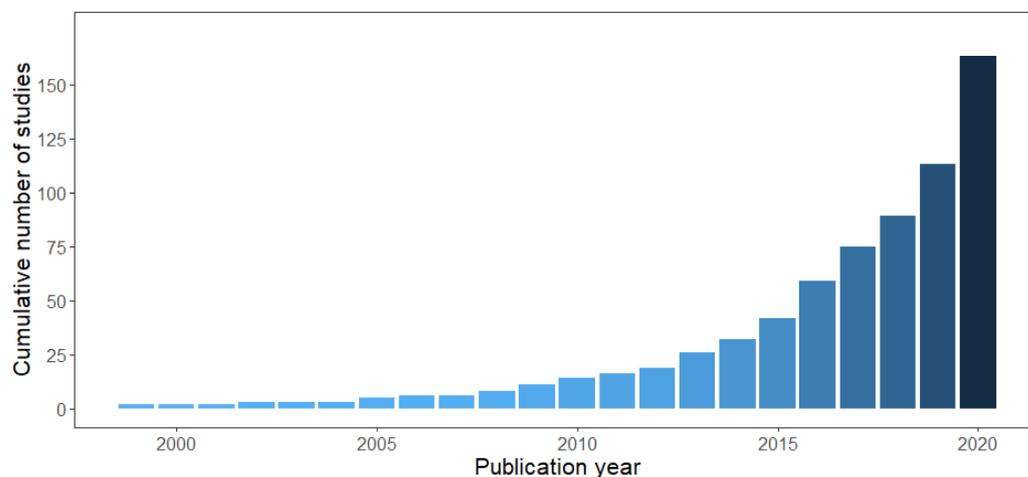


Figure 1. Exponential increase in time of published studies used in our overview (the bar left of 2000 refers to all studies before the year 2000). In total 163 unique studies (peer-reviewed publications) were used: 154 meta-analysis studies and 9 reviews.

2. Materials and Methods

2.1. Data Collection

We reviewed meta-analyses studies related to crop husbandry and soil management practices (henceforth ‘practices’). A total of ten main categories of practices were examined: (1) crop type and crop rotations including intercropping, cover crops, (2) nutrient management, (3) irrigation and fertigation, (4) controlled drainage, (5) tillage practices, (6) pest management, (7) weed management, (8) crop residue management including mulching, (9) mechanization including precision technology, and (10) landscape management, including hedgerows, tree lines, buffer strips. These ten categories of practices relate to the main crop yield defining, limiting, and reducing factors [11,15,16], and with climate-related factors (not included here) have very dominant effects on crop yield and quality, soil quality, and the environmental impacts of crop production.

For each of these categories, quantitative effects of specific practices were distilled from the meta-analysis studies. In most studies, an improved or modified practice was compared with the conventional practice. We focused on the following five outcomes (impacts): (a) crop yield and quality, (b) soil quality, (c) farm income, (d) resource use efficiency, and (e) environmental effects. We attributed the indicators that were used in the meta-analysis to these five outcomes. For crop yield and quality, farm income, and resource use efficiency, a limited number of straightforward indicators were used commonly, but for soil quality and environmental effects a wide range of indicators have been reported. We made no selection in these indicators. We focused on effect sizes defined as the standardized mean difference between the effect of a specific treatment practice relative to that of the control treatment. It is often given as the response ratio (RR) which is the ratio of the effect of a specific treatment (X_t) and the control treatment (X_c), with or without natural log of the ratio.

We collected data from peer-reviewed meta-analysis publications only. The publications were identified using the online database Scopus (<https://www.scopus.com/sources>, accessed on 5 May 2021) within the period 1997–2020. Publications were searched using the keywords “meta-analysis” and the results were refined using additional words—“crop type”, “crop rotation”, “nutrient management”, “fertilization”, “irrigation”, “fertigation”, “drainage”, “tillage”, “pest management”, “disease management”, “weed management”, “crop residue management”, “mulching”, “mechanization”, “landscape management”, “hedgerows”, and “buffer strips”. These keywords were searched for in the title, abstract,

and keywords. Additionally, we used the forward and backward snowballing technique when applicable and a few review studies that presented quantitative data, such as a meta-analysis, were included as well. Further information about the selection and analysis of data is provided in the Supplementary Materials.

A list of abbreviations used in this publication is given in Table A1 (Appendix A).

2.2. Data Compilation and Analysis

Data from the meta-analysis studies were compiled in Windows Excel. The region of the study, the specific practice, the conventional (control) practice, the results, the units and the number of observations were recorded. No further data processing and analyses of the data were undertaken. The Windows Excel database, with all results extracted from the meta-analyses studies, is in the Supplementary Materials.

3. Results

3.1. Overview

Table 1 presents an overview of the meta-analysis studies across categories of practices. Most of the meta-analysis studies dealt with tillage practices (55). Crop type and crop rotations (32), nutrient management (25), irrigation and fertigation (18), and crop residue management (19) have also been analyzed frequently. In contrast, only two studies related to mechanization and (precision) technology.

Table 1. Summary of the number of reviewed meta-analysis studies across crop husbandry and soil management practices, and across aspects (outcome). Note that the sum of the studies for the different aspects can be larger than the number of meta-analysis studies since some studies reported on several aspects.

Crop Husbandry and Soil Management Practices	Number of Meta-Analysis Studies per Aspect					
	Total	Crop Yield & Quality	Soil Quality	Resource Use Efficiency	Economic Aspects	Environmental Impacts
1 Crop type and crop rotations	32	12	12	2	1	14
2 Nutrient management #	25	12	9	0	1	7
3 Irrigation and fertigation	18	12	2	11	0	4
4 Drainage	6	1	1	0	1	4
5 Tillage	55	19	36	5	2	14
6 Pest management	7	3	3	0	0	1
7 Weed management	4	2	2	0	0	0
8 Crop residue and mulching	19	14	5	6	1	8
9 Mechanization and technology	2	3	1	0	1	0
10 Landscape management	6	3	2	0	0	4
Total	174 &	81	73	24	7	56

#: one reference included the human health related aspect survival time of zoonotic pathogens; &: The total number of studies reported here consisted of 163 unique publications, some of which considered more than one crop husbandry or soil management practice.

Most meta-analysis studies examined the effects of specific practices on crop yield and quality (81). For soil quality (73 studies), soil organic matter content was the main focus. For environmental effects (56 studies), the focus was mainly on greenhouse gas emissions and nitrate leaching. Resource use efficiency was examined mainly for irrigation and fertigation, nutrient management and tillage. Only seven meta-analysis studies included economic aspects (Table 1).

The meta-analysis studies reviewed covered a large number of experimental studies and practices in different parts of the world. Each meta-analysis study was based on a large number of underlying studies (on average more than 100; range 8 to 678). In order to attain an impression of how often literature sources have been used in multiple meta-analysis studies, we collected and examined the literature sources of the 55 meta analyses on tillage. In most cases, references to the original studies were provided in the supporting

information, but for seven out of the 55 meta-analyses studies no references were made available. For the remaining 48 studies we collected in total 5465 references to original studies. These were then manually checked on replicate use. Over two-third of these references were used only once, 26% of these were used in two meta-analysis studies, 4% were used three times, and 2% were used four times. Three references were used in seven meta-analyses studies. We conclude that essentially all meta-analyses related to tillage were based on unique studies, which replicated use of original studies is relatively small (given the large number of meta-analyses related to tillage), and that the results of these meta-analyses are largely independent on each other therefore. We did not check repeated use of original studies for other categories of practices.

3.2. Crop Type and Crop Rotation

Selecting the proper crop varieties and crop rotations is often farm and region-specific and key to successful crop farming. Crop rotation is the practice of planting different crops sequentially on the same field, mainly to combat pest and weed pressures and improve soil quality, and thereby to enhance crop yield sustainably. Crop rotations have been the subject of many meta-analysis (Table 1), whereby almost equal attention has been given to crop yield, soil quality, and environmental effects, but little attention to the economic aspects and to resource use efficiency. Specific crop varieties and cultivars have not been the subject of meta-analysis.

Effects of crop rotation, intercropping, and cover crops on crop yield, soil quality, and the environment were positive in almost all studies (Figure 2). Pre-crops before wheat [27] and especially legumes as pre-crops [28] had positive effects on wheat yield, soil quality, and pesticide use [29]. However, effects of pre-crops depend on the nitrogen fertilization rate: yield benefits are highest under low nitrogen fertilization [28]. Indeed, interactions with other crop husbandry and soil management hold for many crop rotation effects; nutrient management, irrigation, pest, disease, and weed management all have a large impact on the effect size of crop rotations [30–32].

The simultaneous cultivation of two or more crop species within one field for at least a part of the growing period (intercropping) also has positive effects on crop yield, but the effect size strongly depends on the crop types and intercropping patterns [30,33]. Growing cover or catch crops after the main crop reduces soil erosion and nitrate leaching and contributes to soil carbon sequestration [34,35], but requires labor and the suppressive effects on pest, diseases and weeds are not always positive. Growing mixtures of varieties of cereals [36] or mixtures of grasses [37] has positive effects on yield (stability) and nitrogen use efficiency.

Effects of crop rotations on GHG emission are variable [38]; this holds also for the effects on cover crops on GHG emissions [39].

3.3. Nutrient Management

The 25 meta-analysis studies related to nutrient management have paid more or less equal attention to crop yield and quality, soil quality, and environmental effects, but little or no attention to economic effects and resource use efficiency (Table 1). Almost all studies reported significant positive effect sizes of the studied nutrient management practices relative to conventional practices (Figure 3).

A main focus has been the characterization of differences between fertilizer types, especially between organic and mineral fertilizers [65,66,78,80] and between 'conventional' fertilizers and fertilizers with inhibitors [71,74], in relation to fertilizer effectiveness, soil quality, and environmental impacts. Deriving the optimal nutrient application rates have been the topic of many experimental studies in the past, and this has also been the subject of several meta-analysis studies [64,68,70]. Better timing of fertilization and placement of fertilizers gave positive effects on yields in most cases [75,84]. Soil liming increased crop yields, especially when pH was low [67]. Positive effects of organic soil amendments and mineral fertilizers on soil biological activity and microbial biomass were found, while

the response of soil enzyme activity depended on enzyme type [68,70,80,81]. Nitrous oxide emissions from cropland increase with nitrogen fertilization, but the increase can be mitigated through better compliance with fertilizer recommendations, and the use of nitrification inhibitors and biochar [72]. Slurry acidification, deep placement, and urease inhibitors decreases ammonia emissions from slurries and urea fertilizers applied to soil [76,86]. No meta-analysis studies related to the effectiveness of manure products from different manure processing techniques [87]. Increasing grazing intensity of pastures increased C, N, and P losses from these pastures ([83] as well as the transfer of zoonotic pathogens to water courses [77]). Only few studies pointed at the effects of interactions between categories of practices, including interactions between intercropping, tillage, and fertilizers types in fruit yield [63], interactions between fertilization, and irrigation in fruit yields [70,88] and in maize yields [70].

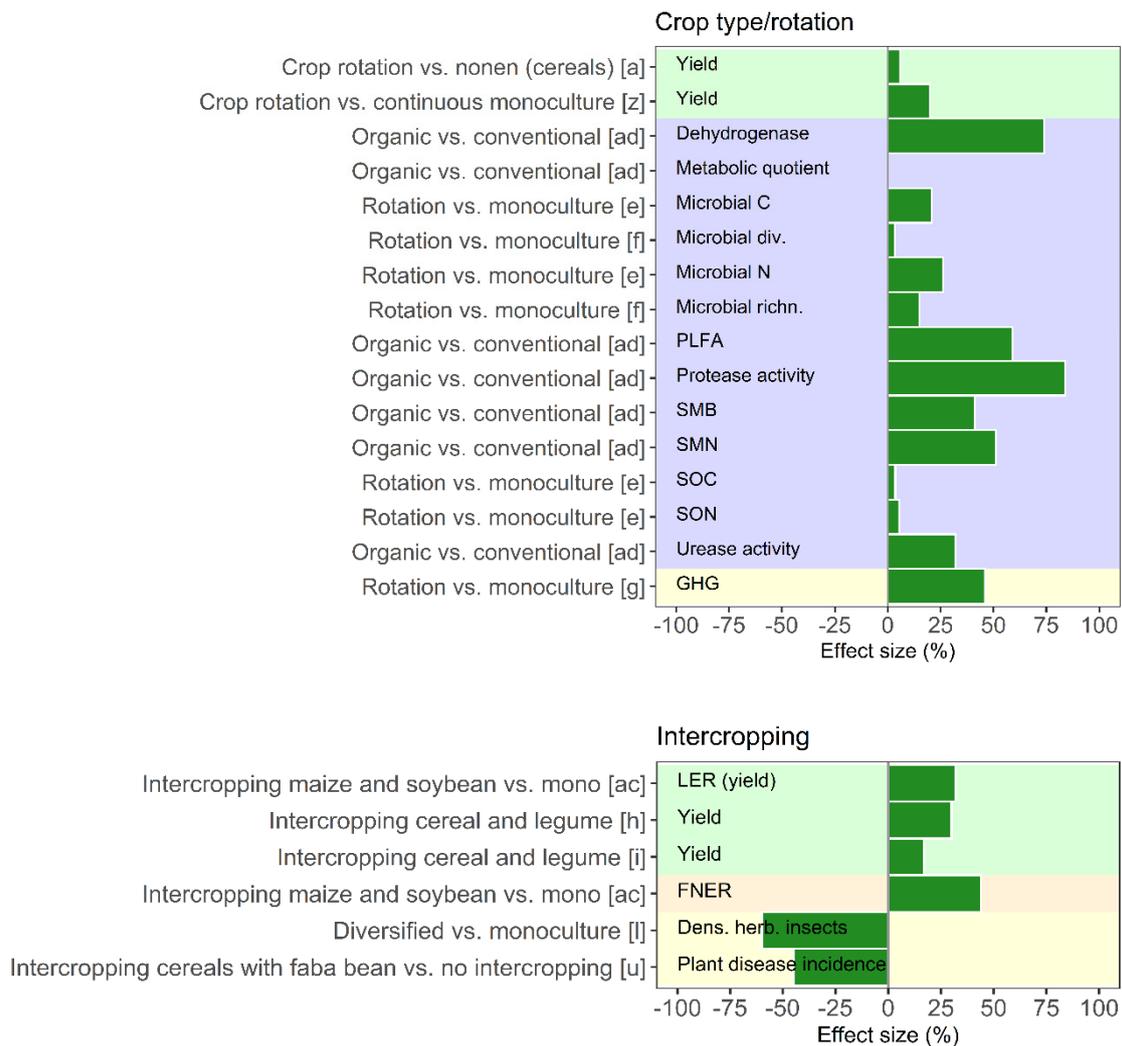


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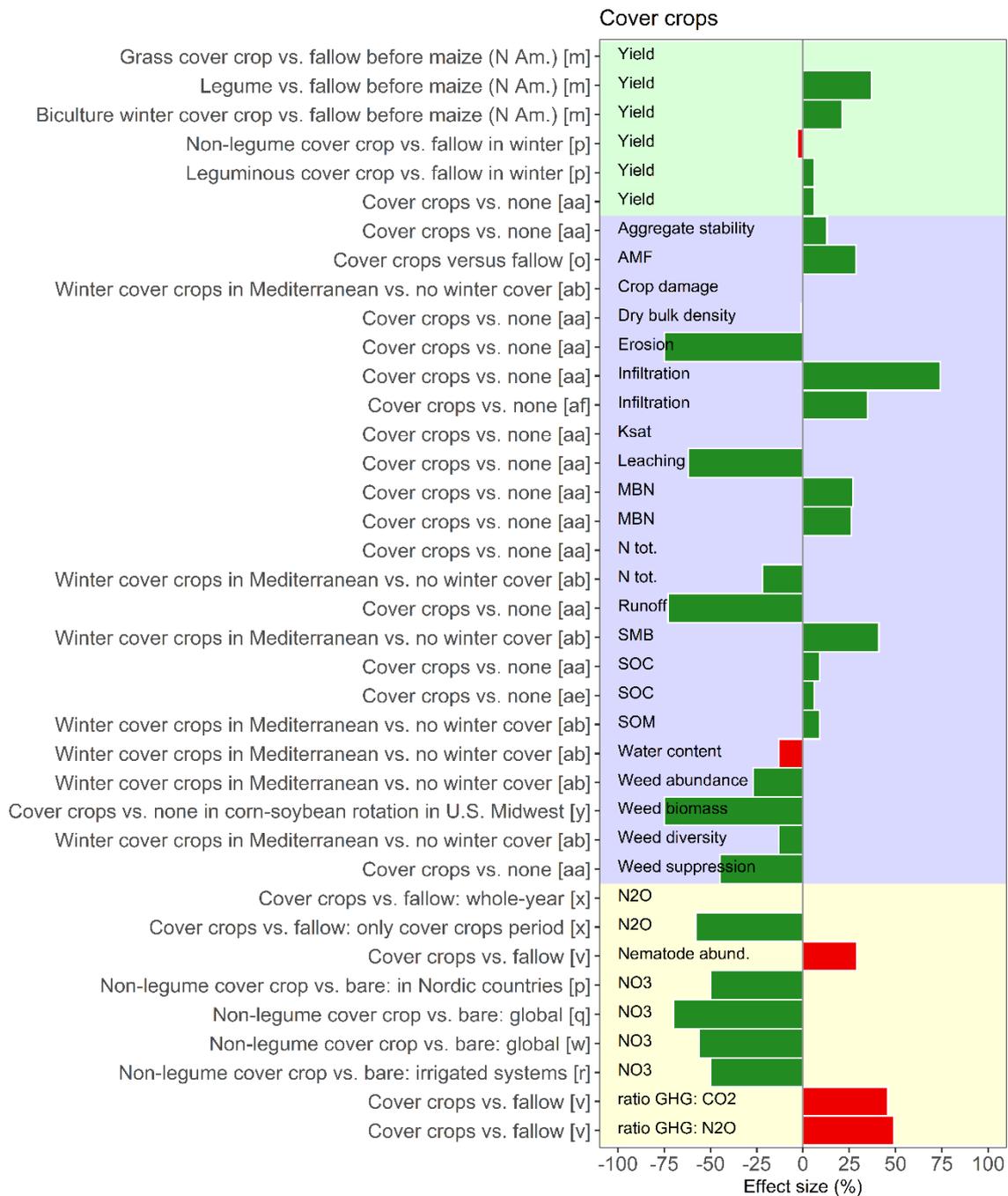


Figure 2. Overall effect sizes (response ratios) reported in meta-analysis studies on cropping (split in crop types and crop rotation, cover crops, intercropping, and perennial crops) grouped per area of interest (light green: agronomic; light blue: soil quality; light orange: resource use efficiency; light brown: economic (no data); light yellow: environmental impacts). The management or treatment comparison is indicated outside the y-axis and the variable to which the data refer are listed inside the y-axis (abbreviations can be found in Table A1). Green bars indicate improvement, red bars indicate worsening. See also Table S1. [a]: [24]; [b]: [28]; [c]: [27]; [d]: [40]; [e]: [41]; [f]: [42]; [g]: [38]; [h]: [43]; [i]: [44]; [j]: [30]; [k]: [45]; [l]: [46]; [m]: [47]; [n]: [48]; [o]: [49]; [p]: [32]; [q]: [31]; [r]: [50]; [s]: [51]; [t]: [52]; [u]: [33]; [v]: [53]; [w]: [54]; [x]: [39]; [y]: [55]; [z]: [56]; [aa]: [57]; [ab]: [58]; [ac]: [59]; [ad]: [60]; [ae]: [61]; [af]: [62].



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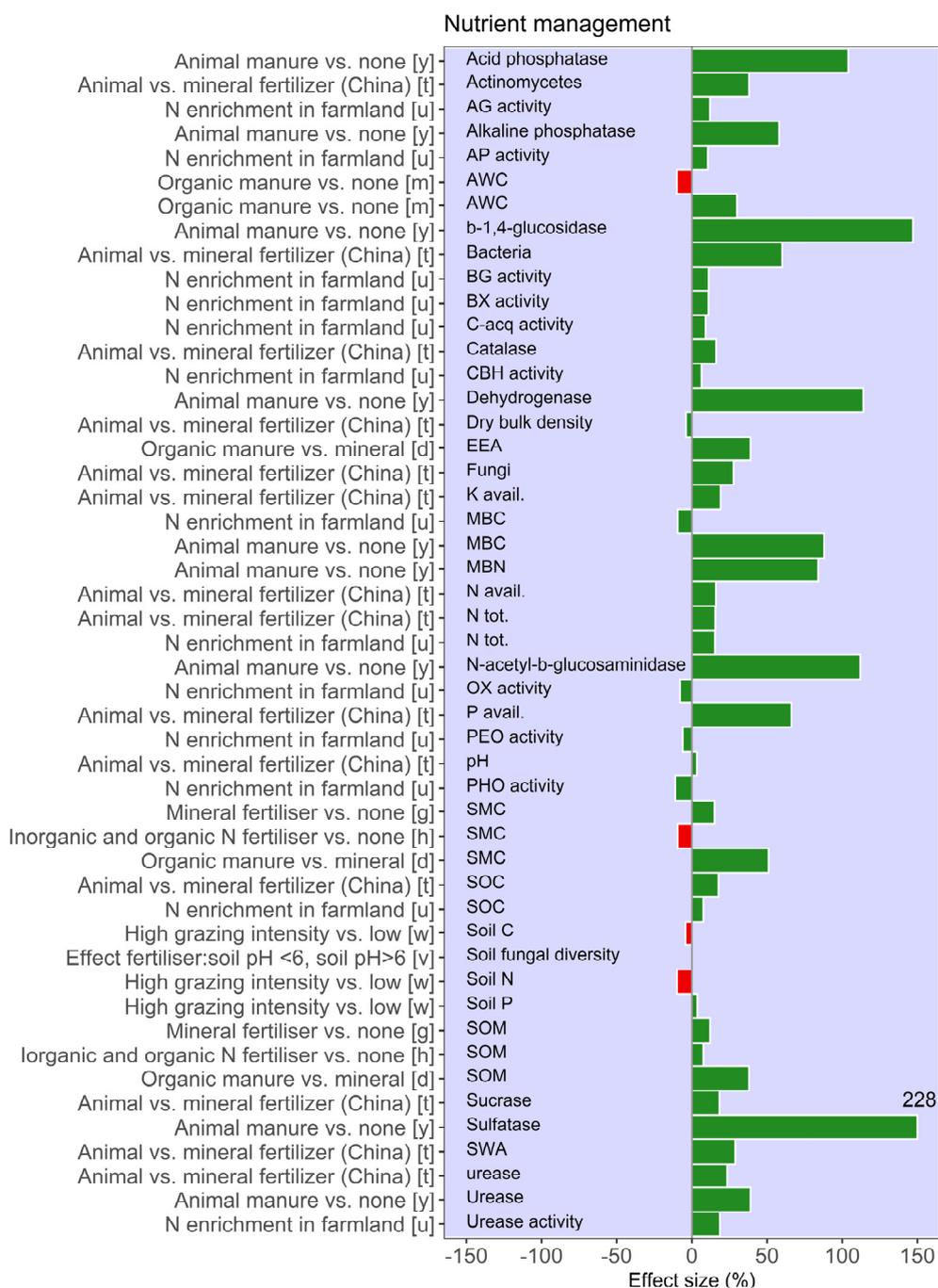


Figure 3. Overall response ratios reported in meta-analysis studies on nutrient management grouped per area of interest (light green: agronomic; light blue: soil quality; light orange: resource use efficiency (no data); light brown: economic (no data); light yellow: environmental impacts). The management or treatment comparison is indicated outside the y-axis and the variable to which the data refer are listed inside the y-axis (abbreviations can be found in Table A1). Green bars indicate improvement, red bars indicate worsening. See also Table S2. [a]: [63]; [b]: [64]; [c]: [65]; [d]: [66]; [e]: [67]; [f]: [68]; [g]: [69]; [i]: [70]; [j]: [71]; [k]: [72]; [l]: [39]; [m]: [73]; [n]: [74]; [o]: [75]; [p]: [76]; [q]: [77]; [r]: [78]; [s]: [79]; [t]: [80]; [u]: [81]; [v]: [82]; [w]: [83]; [x]: [84]; [y]: [85]; [z]: [86].

3.4. Irrigation and Fertigation

A total of 18 meta-analysis studies related to irrigation and/or fertigation, mainly examining the effects of irrigation methods and amounts on crop yield and water use efficiency for different cropping systems and regions (Table 1). The relative strong focus

on water use efficiency reflects that irrigation water is a scarce resource. Most studies reported positive effect sizes of irrigation practices on crop yield and water use efficiency relative to conventional irrigation practices (Figure 4). Effect sizes of water productivity of optimal irrigation and deficit irrigation ranged from 20 to 80%. However, some studies also reported negative effects of deficit irrigation practices relative to conventional irrigation practices, possibly because irrigation was reduced too much in deficit irrigation treatments.

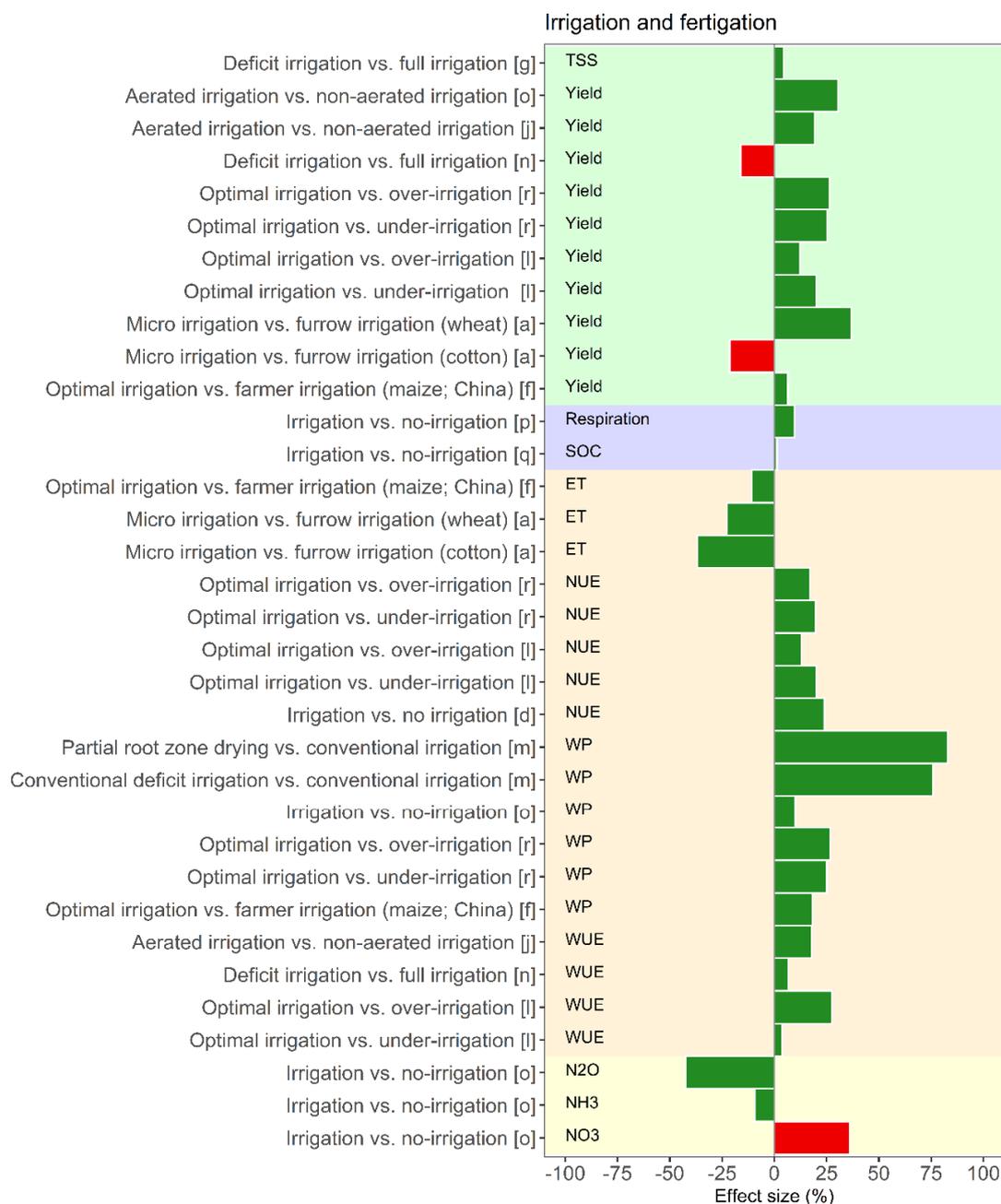


Figure 4. Overall response ratios reported in meta-analysis studies on irrigation and fertigation grouped per area of interest (light green: agronomic; light blue: soil quality; light orange: resource use efficiency; light brown: economic (no data); light yellow: environmental impacts). The management or treatment comparison is indicated outside the y-axis and the variable to which the data refer are listed inside the y-axis (abbreviations can be found in Table A1). Green bars indicate improvement, red bars indicate worsening. See also Table S3. [a]: [94]; [b]: [90]; [c]: [95]; [d]: [96]; [e]: [91]; [f]: [97]; [g]: [98]; [h]: [99]; [i]: [89]; [j]: [100]; [k]: [101]; [l]: [88]; [m]: [102]; [n]: [103]; [o]: [104]; [p]: [92]; [q]: [93]; [r]: [70].

Two meta-analysis studies examined the effects of irrigation method on emissions of N_2O [89,90], while one study examined flood irrigation practices on emissions of methane from paddy rice [91]. Two studies examined effect of irrigation on soil respiration and soil carbon contents [92,93]. Only two studies pointed at large effects of interactions between irrigation and fertilization in water use efficiency and nutrient use efficiency [70,88].

3.5. Controlled Drainage

Effects of controlled drainage on the loss of water, nutrients, and greenhouse gases were assessed through six meta-analysis studies (Table 1). Controlled drainage is defined as the use of adjustable head structures to prevent discharge when the water table is lower than the outlet elevation. In this way the loss of water and nutrients may be altered, depending on the target. The quantitative effects of controlled drainage on reducing drainage volumes, N losses, and methane emissions were relatively large (range 17 to 85%) (Table 2). Generally, controlled drainage resulted in reduced drainage volumes, depending on soil type [105]. Controlled drainage also reduced N-losses via drainage water to surface water [106–108] and methane (CH_4) emissions from peat lands [109]. No impact on yield was found by [108]. Alternating wetting and drying cycles in paddy rice greatly decreased CH_4 emissions, but increased N_2O emission; yet total greenhouse gas emissions decreased through improved water management [110].

Table 2. Controlled drainage: effect sizes as reported in meta-analysis studies. See also Table S4.

Parameter	Comparison of Treatments	Main Results
Yield	Drainage vs. none	not significant [e]
Economic benefit	Drainage vs. none	9 to 37 \$ ha ⁻¹ yr ⁻¹ [c]
CH ₄ emission from paddy rice field	Wetting and drying vs. continuous flooding	−35% [f]
CH ₄ emission from peat	Drainage vs. none	−29% for CH ₄ +N ₂ O (net GWP) [f]
Drainage volume	Drainage vs. none	−84% [a]
N-load	Drainage vs. none	−47% [b]; −17% to −85% [d]; −19% [e]
P-load	Drainage vs. none	−41% [c]; −18% to −85% [d]; −32% [e]
		−19% [e]

[a]: [109]; [b]: [105]; [c]: [106]; [d]: [107]; [e]: [108]; [f]: [110].

3.6. Tillage

Tillage refers to the preparation of the soil for growing crops, with or without incorporation of crop residues in the soil and/or weed control. In conventional or traditional tillage (TT), the topsoil (usually the upper 15 to 25 cm) is turned and/or milled. Conservation tillage (including no-tillage (NT) or reduced tillage (RT)) is the practice of minimizing soil disturbance, whereby crop residues commonly remain on the soil surface to protect the soil, while herbicides or precision mechanical weeding tools are used to control weeds. Tillage practices are debated because of high fossil energy and labor costs, and their effects on soil erosion, crop yield, soil organic carbon, and soil biodiversity. This debate is reflected in the high number (55) of meta-analysis studies (Table 1). The focus of most meta-analysis studies has been on soil quality (36), followed by crop yield effects (19) and environmental effects (14). Two studies synthesized economic implications of different tillage practices (Table 1). Of the total number of studies, 20 were global studies, 14 studies related to (parts of) China, 5 to the Mediterranean, 3 to US, 1 to South Asia, 1 to Brazil, 1 to Europe and none to Africa.

Overall, conservation tillage decreased crop yields, increased soil organic carbon contents in the topsoil, increased soil biodiversity and the abundance of soil organisms, and increased N_2O emissions relative to conventional tillage, but the magnitude of the differences depended on climate and the particular study (Figure 5). Yield penalties of no-till depended on crop residue return and crop rotation and were larger in tropical than temperate regions, and tended to decrease with an increase in the duration of no-till [22,111]. The South-Asian study was probably the most integrated one, as it examined effect sizes of crop yield, water use, soil organic C sequestration, emissions of CO_2 , CH_4 , and N_2O ,

and economic costs [112]. The cost of production was significantly lower under no-till than under conventional tillage in all the selected crops, and the net economic returns increased by 5 to 32%. Manley et al. [113] examined the economic cost of soil carbon sequestration in the US through no-till. They found that the additional carbon sequestration of no-till compared to conventional till was small and variable, and as a result, the net economic benefit also varied widely.

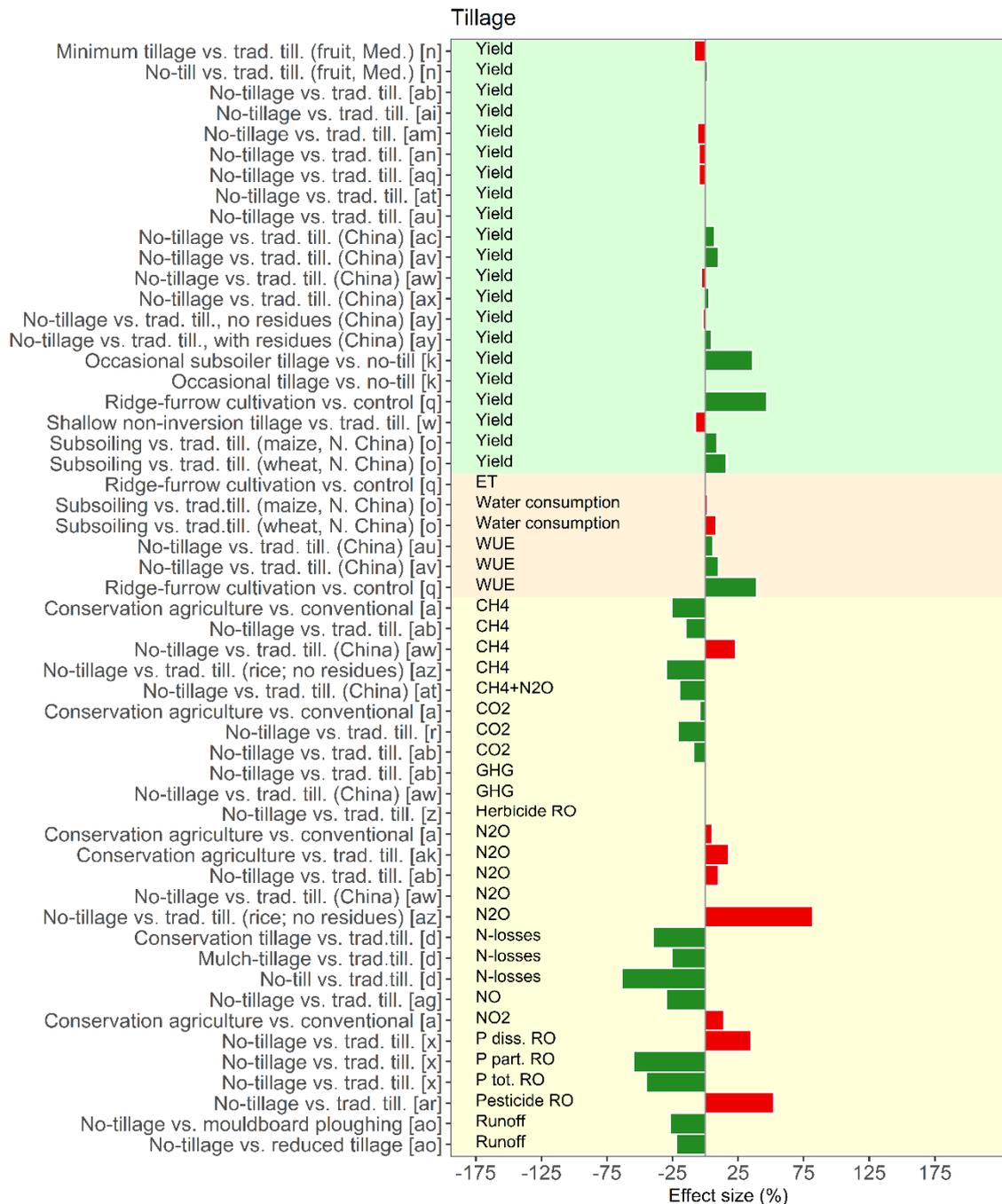


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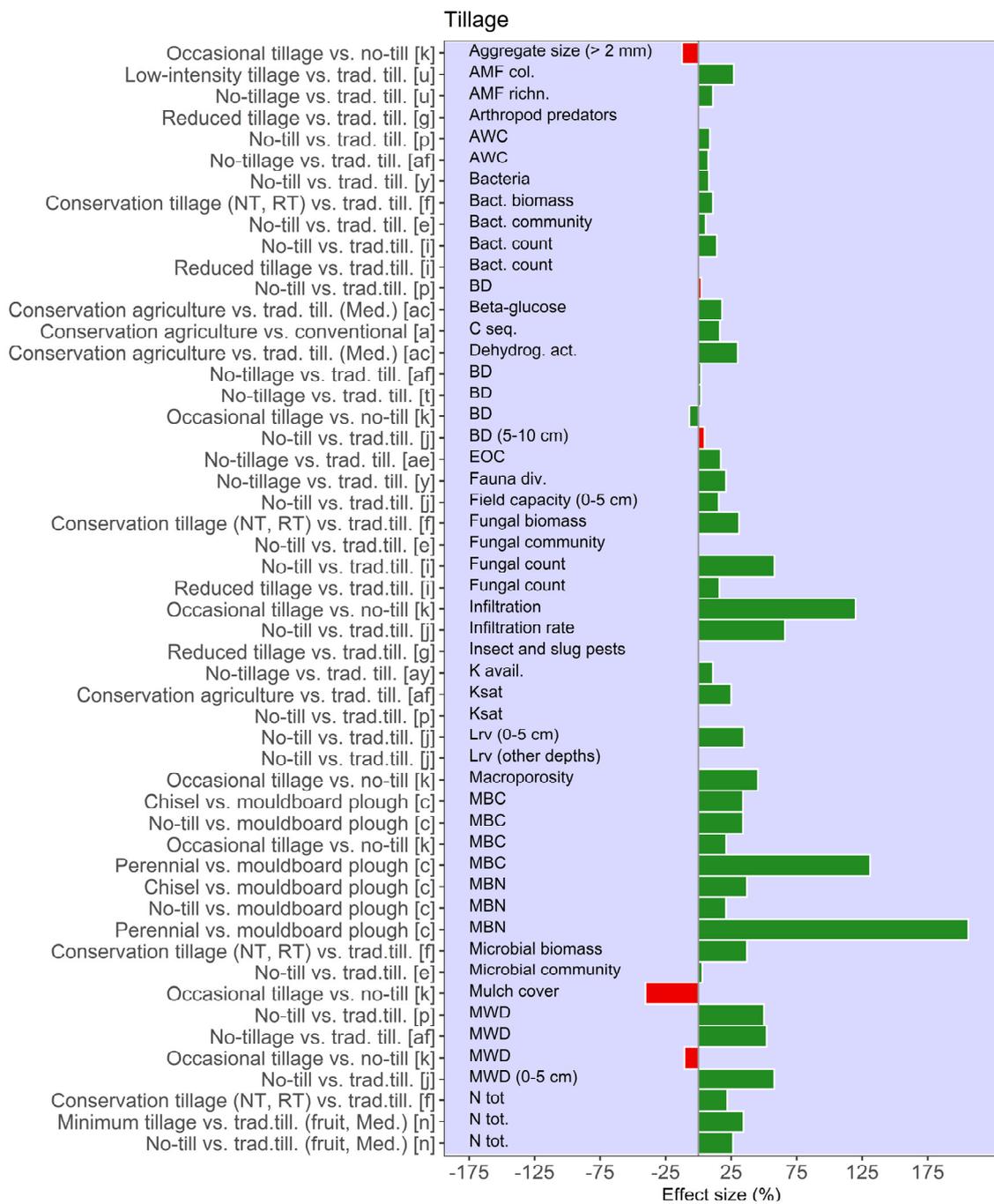


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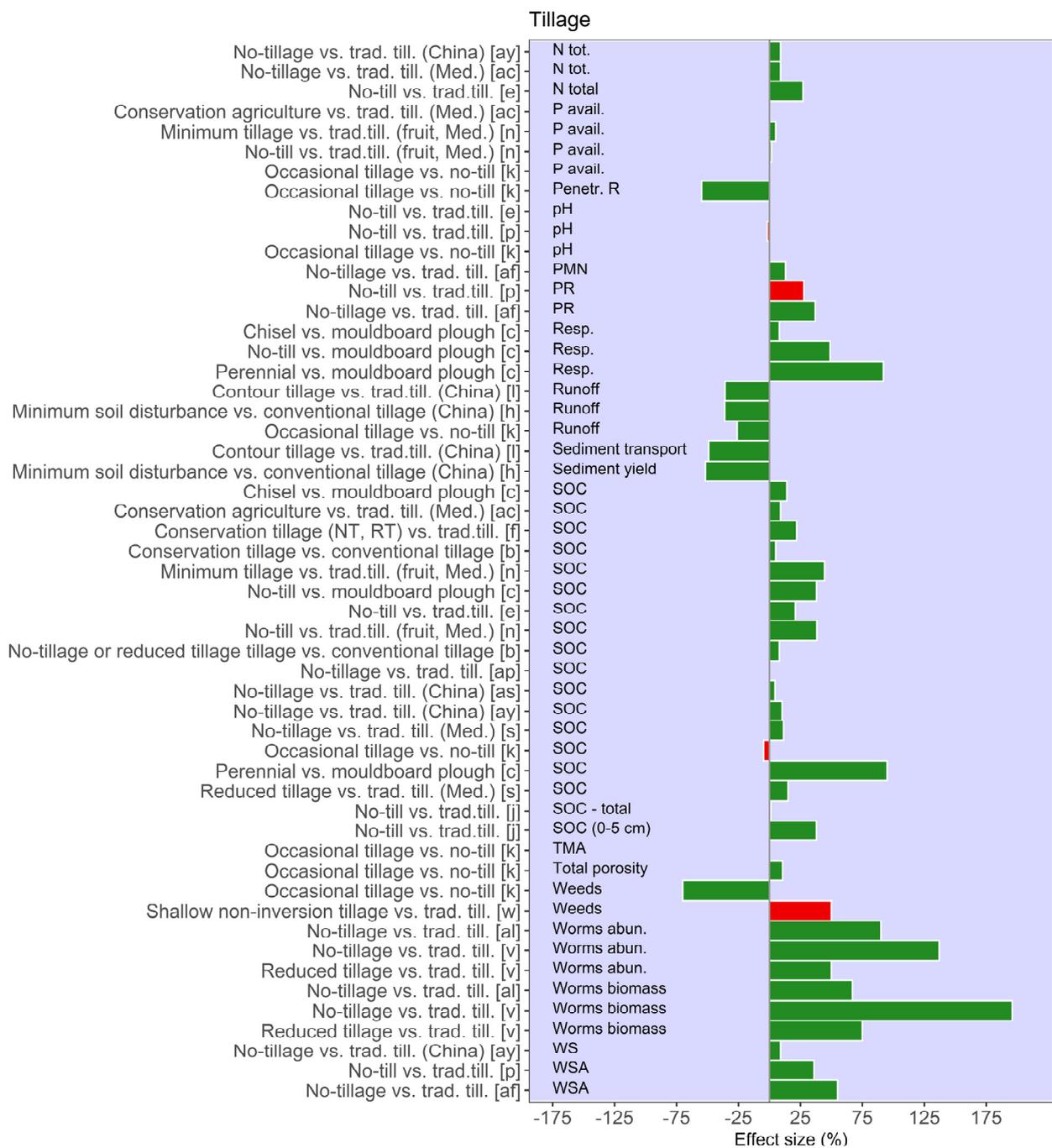


Figure 5. Overall response ratios reported in meta-analysis studies on tillage grouped per area of interest (light green: agronomic; light blue: soil quality; light orange: resource use efficiency; light brown: economic (no data); light yellow: environmental impacts). The management or treatment comparison is indicated outside the y-axis and the variable to which the data refer are listed inside the y-axis (abbreviations can be found in Table A1). Green bars indicate improvement, red bars indicate worsening. See also Table S5. [a]: [112]; [b]: [61]; [c]: [123]; [d]: [123]; [e]: [124]; [f]: [125]; [g]: [124]; [h]: [120]; [i]: [115]; [j]: [118]; [k]: [119]; [l]: [126]; [m]: [127]; [n]: [63]; [o]: [128]; [p]: [129]; [q]: [130]; [r]: [131]; [s]: [132]; [t]: [133]; [u]: [49]; [v]: [114]; [w]: [134]; [x]: [53]; [y]: [135]; [z]: [122]; [aa]: [136]; [ab]: [137]; [ac]: [138]; [ad]: [139]; [ae]: [140]; [af]: [117]; [ag]: [74]; [ah]: [141]; [ai]: [142]; [aj]: [113]; [ak]: [143]; [al]: [116]; [am]: [111]; [an]: [22]; [ao]: [121]; [ap]: [144]; [aq]: [24]; [ar]: [145]; [as]: [146]; [at]: [147]; [au]: [148]; [av]: [149]; [aw]: [150]; [ax]: [151]; [ay]: [152]; [az]: [153].

Several studies found positive effect sizes of no-till versus conventional till for number of earthworms and for the diversity of the (micro) biological community (e.g., [114–116]). No-till tended to increase the bulk density in the lower part of the topsoil (10–20 cm) and the water infiltration rate significantly [117,118]. However, no-till combined with occasional conventional tillage decreased soil bulk density compared to conventional tillage [119]. Effects of no-till on erosion are strongly affected by crop type and soil surface mulching; on average no-till and conservation agriculture reduced erosion [120,121], but pesticides in runoff tended to increase [122].

3.7. Pest Management

Pest management refers to the control of the number of undesirable organisms (pathogens, pest organisms) below an acceptable threshold, which is often based on economic principles. Methods of control can be crop rotation, chemical, biological, physical/mechanical, and/or genetic. There are often interactions with crop residue management, tillage, nutrient management, irrigation, and landscape management [154]. We found seven meta-analysis studies related to pest management (Table 1), of which three were in the context of comparing organic versus conventional agriculture (Table 3). Muneret et al. [155] found that organic farming experiences higher levels of pest infestation, but is able to match or outperform conventional pest control practices against plant pathogens and animal pests. Lesur-Dumoulin et al. [156] found that yields in organic horticulture were on average 10 to 32% lower than yields in conventional horticulture (Table 3). Garratt et al. [157] observed that organic farming practices can increase natural enemy numbers and also pest responses. Fertilization tends to increase insects and fungal plant pathogens [158,159]. Biofumigation through incorporating Brassicaceae plants and crop residues, which release glucosinolates and isothiocyanates, in soil reduced pest abundance and subsequently increased crop yield by 30% [160]. Anaerobic soil disinfestation, through temporal soil sealing following incorporation of labile organic carbon in the soil, is also effective against soil borne pathogens [161]. Furthermore, it has been indicated that addition of organic amendments and improving soil quality and biodiversity may result in fewer pests [162].

Table 3. Pest management: main effects as reported in meta-analysis studies. See also Table S6.

Parameter	Management Practices	Result
Yield	Biofumigation	Abs. diff.: 29% [a]
Yield	Anaerobic soil disinfestation	Abs. diff.: 30% [b]
Suppression of pathogens	Anaerobic soil disinfestation	Abs. diff.: 70% [b]
Yield	Organic/conventional	Ratio: 0.83 [c]
Disease severity response by fungal plant pathogens	Fertilized vs. unfertilized	Increase 0.3 ± 0.1 [d]
Change in insect population	Fertilization	Increase/decrease 175/78 [e]
Change in pest population	Organic/non-organic	Increase/decrease 42/26 [f]

[a]: [160]; [b]: [161]; [c] [156]; [d]: [159]; [e]: [158]; [f]: [157].

3.8. Weed Management

Weed management refers to the control of the number of weed plants (especially noxious weeds) to below an acceptable threshold, as weeds compete with the crop for light, water and nutrients. Weed management often includes a number of methods, including crop rotation/intercropping/cover crops, soil cultivation (weeding, hoeing), mulching (crop residues or plastic covers), herbicides spraying, and burning. We found four meta-analysis studies related to weed control (Table 2).

Verret et al. [163] found that intercropping with legume companion plants enhanced weed control, generally without reducing the yield of the main crop (Table 4). Cover crops can also decrease the incidence of weeds and may have other ecosystem services [164]. Crop rotation with different planting dates and crop diversification, combined with limited soil disturbance, can disrupt weed-crop associations in addition to reducing yield loss and rebuilding soil fertility [165–167]. Glyphosate is the most used chemical weed control

agent [168], but is debated because of its effects on soil biodiversity and soil microbial respiration [169] and human health [168].

Table 4. Weed management: main effects as reported in meta-analysis studies. See also Table S7.

Parameter	Comparison of Treatments	Result
Weed biomass	Legume intercropping vs. conventional, both non-weeded and weeded	−56%, −42% [a]
Weed density, biomass Parasitic nematodes	Cover crops vs. traditional tillage	−10%, −5%, +29% [b]
Number of studies with increase soil organic matter	Reduced tillage vs. traditional tillage	+40 and −7 out of 78 studies [c]
Soil microbial respiration	Glyphosate vs. no use, <10 mg kg	logarithm of ratio:
Soil microbial biomass	Glyphosate vs. no use, >10 mg kg	0.064 ± 0.126 , 0.04 ± 0.09 [d]

[a]: [163]; [b]: [53]; [c]: [170]; [d]: [169].

3.9. Crop Residue Management

Crop residues may be left on the soil surface, incorporated in the soil, burned or removed from the field for use as livestock feed or biofuel. Evidently, there are trade-offs in managing crop residues [171]. Conservation agriculture promotes the return of the crop residues to the soil to increase soil quality and reduce soil erosion, often in combination with zero-tillage or reduced tillage (Section 3.6). In this review, we distinguished crop residue management as a separate management practice, because of the relatively large number (19) of meta-analysis studies related to just crop residues (Table 1). Crop yield, water and nitrogen use efficiency, emissions of N₂O, and soil carbon sequestration were the main topics of these studies.

In most cases, crop residue management and mulching increased crop yields, and water and nitrogen use efficiencies by 0 to 50% (Figure 6). Mulching greatly reduced soil evaporation and thereby provided a greater fraction of soil water to the crop, which boosted crop yields. Crop residue return has a positive effect on soil carbon sequestration and soil microbial activity, but N₂O emissions increased as well. Nine out of the 19 meta-analysis studies dealt with soil mulching effects in China, as it is a common practice in dry-land farming in China (and India). One study examined the performance of biodegradable plastics to determine the optimal type of mulching for maize, wheat, potato, and cotton [172], and another [173] compared the performance of biodegradable films relative to polyethylene films.

3.10. Mechanization

Mechanization has greatly increased labor productivity in modern crop production systems, especially during the last century, and thereby has greatly contributed to farm-scale enlargement and withdrawal of labor from agriculture [189]. However, mechanization has also contributed to increased fossil fuel use and increased soil compaction [190]. During the last decades, research emphasis has shifted to precision technology, controlled traffic, and robotization. However, only two meta-analysis studies have touched mechanization, precision technology and robotization (Table 1). Ampoorter et al. [191] concluded on the basis of an analysis of 11 studies with 35 forest stands that mechanical harvesting of trees has led to the compaction of the top 30 cm of forest soils, with the largest effects on the top 10 cm. One study was of a different nature: It examined the change in the ratio of maize grain yield to labor input following the introduction of specific sustainable intensification practices technologies in sub-Saharan countries [192]. No firm conclusions could be derived because of lack of sufficient empirical studies.

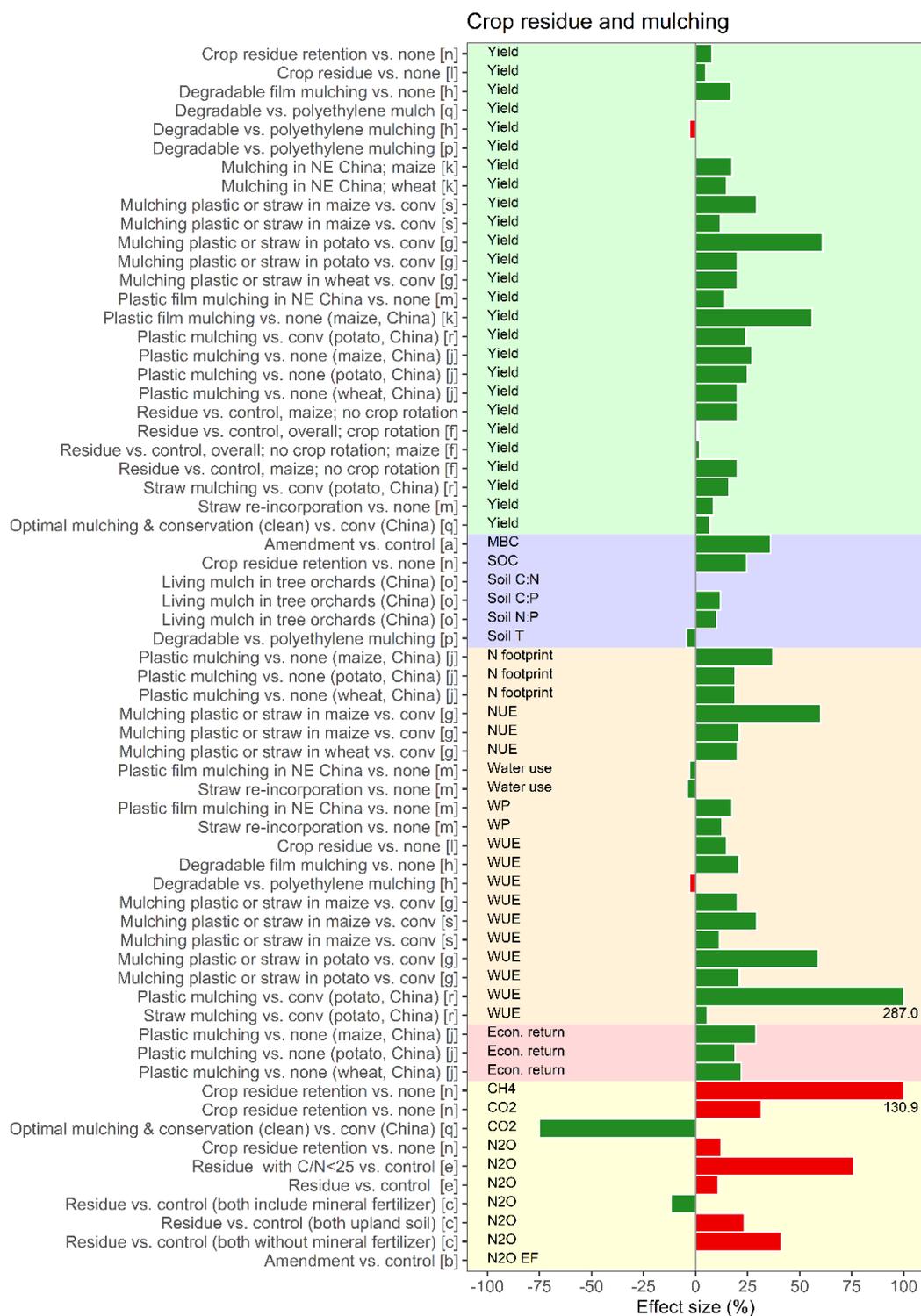


Figure 6. Overall response ratios reported in meta-analysis studies on crop residues and mulching grouped per area of interest (light green: agronomic; light blue: soil quality; light orange: resource use efficiency; light brown: economic; light yellow: environmental impacts). The management or treatment comparison is indicated outside the y-axis and the variable to which the data refer are listed inside the y-axis (abbreviations can be found in Table A1). Green bars indicate improvement, red bars indicate worsening. See also Table S8. [a]: [174]; [b]: [175]; [c]: [176]; [d]: [177]; [e]: [178]; [f]: [22]; [g]: [179]; [h]: [172]; [i]: [180]; [j]: [181]; [k]: [182]; [l]: [183]; [m]: [97]; [n]: [184]; [o]: [185]; [p]: [173]; [q]: [186]; [r]: [187]; [s]: [188].

3.11. Landscape Management

Landscape management is a relatively new concept and has increased in importance following the approval of the UN Sustainable Development Goals and the recognition that the landscape is often the best scale for managing interactions, synergies, and trade-offs for natural resource management [193–195]. Landscape management in the context of sustainable food production may include hydrological measures, terracing, hedgerows, tree lines, wind breaks, flower strips, corridors, and agroforestry, depending on the landscape, environmental conditions, and stakeholders.

We identified six meta-analysis studies related to landscape management practices (Tables 1 and 5). Three of these quantified the benefits of windbreaks on crop yields [196–198]. Three studies analyzed the effects of hedgerows and flower strips on pollination, pest control, and crop yield [197–199], and two studies analyzed the effects of hedgerows on runoff and erosion [198,200]. Both large positive effects and negative effects have been reported (Table 5).

Table 5. Landscape management: summary of the results as reported by meta-analysis studies. See also Table S9.

Parameter	Management Practices	Result
Crop yield increase	Wind breaks	Spring wheat +8%, winter wheat +23%, barley +25%, oats +6%, rye +19%, millet +44%, corn +12%, alfalfa +99%, hay +20% [a]
Crop yield	Hedgerows vs. control; next to hedge until twice the height; beyond twice the height until 20 times the height	−29%, +6% [b]
Soil organic matter in crop field	Hedgerows vs. control	6% [b]
Interception of N, P, suspended solids from soil surface flow	Hedgerows Grass strips	69%, 67%, 91% [b] 67%, 73%, 90% [b]
Crop yield	Hedge rows, flower strips vs. none	ns [c]
Pest control	Hedge rows, flower strips vs. none	ns, −16% [c]
Pollination	Hedge rows, flower strips vs. none	ns [c]
Abundance, richness of pollinators in crop	Flower strips vs. none	ns, ns [d]
Pollinator species richness	Effect of agri-environment management, type landscape:	Hedge's d:
	Small, simple	sign. [f]
	Small, complex	ns [f]
	Large, simple	sign. [f]
Soil SOM, total N, total P, alkali N, available P, readily available K, total K	Hedge rows vs. none	Hedge's d sign. [e]
		Hedge's d ns [e]

[a]: [196]; [b]: [198]; [c]: [197]; [d]: [199]; [e]: [200]; [f]: [201].

4. Discussion

4.1. Main Findings

Most meta-analysis studies reported positive effects of alternative/improved practices relative to conventional practices. The 32 studies related to crop type and crop rotation clearly indicated the positive effects of crop rotations versus continuous cropping, legumes in crop rotations versus no legumes in crop rotations, intercropping versus monocultures, and cover cropping versus no cover cropping on crop yield and soil quality. Positive effects of especially cover crops and perennial crops on erosion control and minimizing nitrate leaching were also found, depending on, e.g., N fertilization.

The 25 studies related to nutrient management examined a diversity of nutrient sources, and application methods, timing, and strategies. Most studies reported positive effects of alternative/modified practices on crop yield and on minimizing environmental

pollution, relative to conventional practices. Impacts of nutrient management strongly depended on environmental conditions.

The 18 studies related to irrigation and fertigation focused on the method, timing and volume of irrigation. Drip irrigation, deficit irrigation, and subsoil irrigation were all effective in increasing water use efficiency compared to sprinkling irrigation and especially flood irrigation. No economic assessments were made, and long-term impacts on soil quality and environmental pollution were also not reported.

Six studies related to drainage, with a focus on controlled drainage in response to variable rainfall patterns. Results indicate that controlled drainage increased farm income when compared to no human-induced drainage.

A total of 55 meta-analysis studies were devoted to tillage practices. Reduced tillage tended to reduce crop yields, but increased farm income (one study only), water use efficiency, soil carbon contents, and emissions of nitrous oxide (N₂O), which is a potent greenhouse gas. Reduced tillage in combination with crop residue return (mulching) and crop rotation had a slight positive effect on crop yield compared to conventional tillage.

Most of the seven studies related to pest management compared organic farming and conventional farming management practices. In general, organic farming management practices greatly decreased the use of pesticides, but lowered crop yields as well, depending on crop type and rotation, N application rate, soil quality, and (soil) biodiversity.

The four studies related to weed management did not provide a coherent view. Legume intercropping, cover cropping, and reduced tillage had positive effects on soil carbon contents but the effects on weed and crop yield were not clear.

The 19 studies related to crop residue management and mulching in dryland and/or irrigated conditions reported in general positive effects of mulching on crop yield and water use efficiency, but also increases in N₂O emissions, which are unwanted.

The six studies related to landscape management reported positive effects of windbreaks and hedgerows on crop yields and erosion control, but depending on site specific conditions, and provided that the surface area of windbreaks and hedgerows is in balance with the cropping area.

Evidently, most of the studies reported positive effects of the examined alternative/improved practices, relative to the common practice, on either crop yield, soil quality, resource use efficiency, and the environment (decreased emissions). While global assessment studies often paint rather pessimistic views on the state of food production, agriculture, and the environment [10,16,202–204], it is clear that the 174 studies reviewed here present a picture of optimism and hope. Indeed, there is large body of scientific/empirical evidence that some specific practices are more effective than others, i.e., have positive effect sizes relative to conventional practices (Figures 1–6; Tables 2–5), and that these positive effects may contribute to the sustainability of crop and food production. However, large steps still have to be made to integrate, optimize, and transfer the scientific findings of meta-analysis in current practice. We note that only few meta-analysis studies examined interactions between categories of practices, while essentially no meta-analysis study made in-depth comparisons at cropping system level in which all ten categories of crop husbandry and soil management practices had been optimized. Hence, there is need for further integration and optimization of all ten crop husbandry and soil management practices, and show the effectiveness of optimized practices through experimental studies and ultimately meta-analysis studies. There is also a need to transfer the positive messages of meta-analysis studies to practice through demonstration, extension services and possibly economic incentives. Cropping systems with all crop husbandry and soil management practices optimized may be termed ‘soil-improving cropping systems’, to emphasize the two-way interaction between soil and crop (see Section 4.3).

4.2. Uneven Coverage of Meta-Analysis Studies

Some crop husbandry and soil management practices have been studied extensively and repeatedly, while some other practices have received little research attention (Table 1).

Further, most studies have examined the effects of practices on crop yield, soil quality and environmental effects, while farm income (cost-benefit ratios) and resource use efficiency have received less attention (and human health aspects not at all). Evidently, the coverage of meta-analysis studies across practices and outcomes has been uneven; 75% of all studies addressed four practices, in the order: soil tillage > crop type and crop rotations > nutrient management > irrigation/fertigation (Table 1).

The large interest in soil tillage (55 meta-analyses studies) is certainly related to the importance of soil conservation, and the envisaged reduction in soil erosion, net greenhouse gas emissions, energy use, and labor through minimum or zero tillage. The effect-size of tillage practices were relatively small (0–10%) for crop yield, modest (0–50%) for greenhouse gas emissions and nutrient leaching, and relatively large and positive for soil quality, especially for soil life (0–150%).

The relatively large attention for nutrient management and irrigation/fertigation is related to the role of nutrients and water in boosting crop yields across the world (e.g., [205], to the depletion of fresh water resources [206] and rock phosphorus resources [207,208], and to the ecological impacts of excess nitrogen and phosphorus in the environment [16,209]). Nutrient and irrigation water inputs often form a relatively large economic cost to farmers, especially in developing countries, but this aspect has not been addressed.

We found only two meta-analyses related to mechanization and technology in agriculture (including forestry). However, several recent textbooks on precision technology for cropping systems do address the possible economic and environmental impacts of technological applications for sensing, field operations, and data handling, analysis, and control (e.g., [210–212]). Indeed, mechanization has revolutionized crop production systems during the past century but differently in different regions of the world. It has made large-scale crop production systems possible, has led to an exodus of laborers, has contributed to international trade of food and feed, and has indirectly affected essentially all crop husbandry and soil management practices. Robotization goes a step further and may revolutionize crop production systems again in the near future; it also offers the opportunity to reduce the impact of heavy machines on soil compaction. Keller et al. [190] estimated that the increase in weight of agricultural vehicles has caused an increase in soil bulk density, and thereby decreased root growth, crop yields, and soil hydraulic properties. They speculate that heavy machinery has contributed to yield stagnation and increased flooding in Europe [190].

We recommend that future meta-analysis studies related to crop husbandry and soil management practices should pay more attention to the socio-economic impacts of practices including possible barriers and constraints for their implementation in practice. Next, we recommend that more emphasis has to be given to interactions between multiple crop husbandry and soil management practices, and to comparisons of region-specific optimized packages of these practices. Further, Africa should not be neglected, as much of the increased food demand (and food production) during the next few decades will occur in Africa.

4.3. Towards High-Yielding, Soil-Improving, and Environmentally Sound Cropping Systems

The effect of specific crop yield defining, yield limiting, or yield reducing factors is largest when all other crop yield defining, limiting, or reducing factors are optimal, i.e., at a level where these do not affect crop yield [213]. This ‘law of the optimum’ may have also influenced the outcomes of meta-analyses studies; optimality of all factors will have enhanced the effect size of an alternative practice relative to the control practice, and vice versa. We have no insight in the degree of optimality of yield factors in the studies underlying the reviewed meta-analyses, but simply note here that there is often a gap between actual and attainable yields, and between actual and attainable environmental performances in practice. These gaps have to be narrowed to be able to produce adequate amounts of food in a sustainable and region-specific way [214].

The reviewed meta-analysis studies provide many suggestions for improved practices, but the optimization of all practices has to be done for specific regions, at farm level and/or regional levels. The possible steps in the optimization process have been summarized in Figure 7; it provides a roadmap for developing high-yielding, soil-improving and environmental-sound cropping systems. Steps 1 and 2 deal with the analyses and description of the current cropping systems, including its socio-economic and environmental environments. Steps 3 to 12 then deal with the selection and optimization of the 10 main specific crop husbandry and soil management practices, while taking the results of steps 1 and 2 into account. The actual process of optimization will be iterative, until the most optimal combination of practices has been identified. Variants of this road-map have been tested within the EU-funded project SoilCare, and results are presented in this special issue.

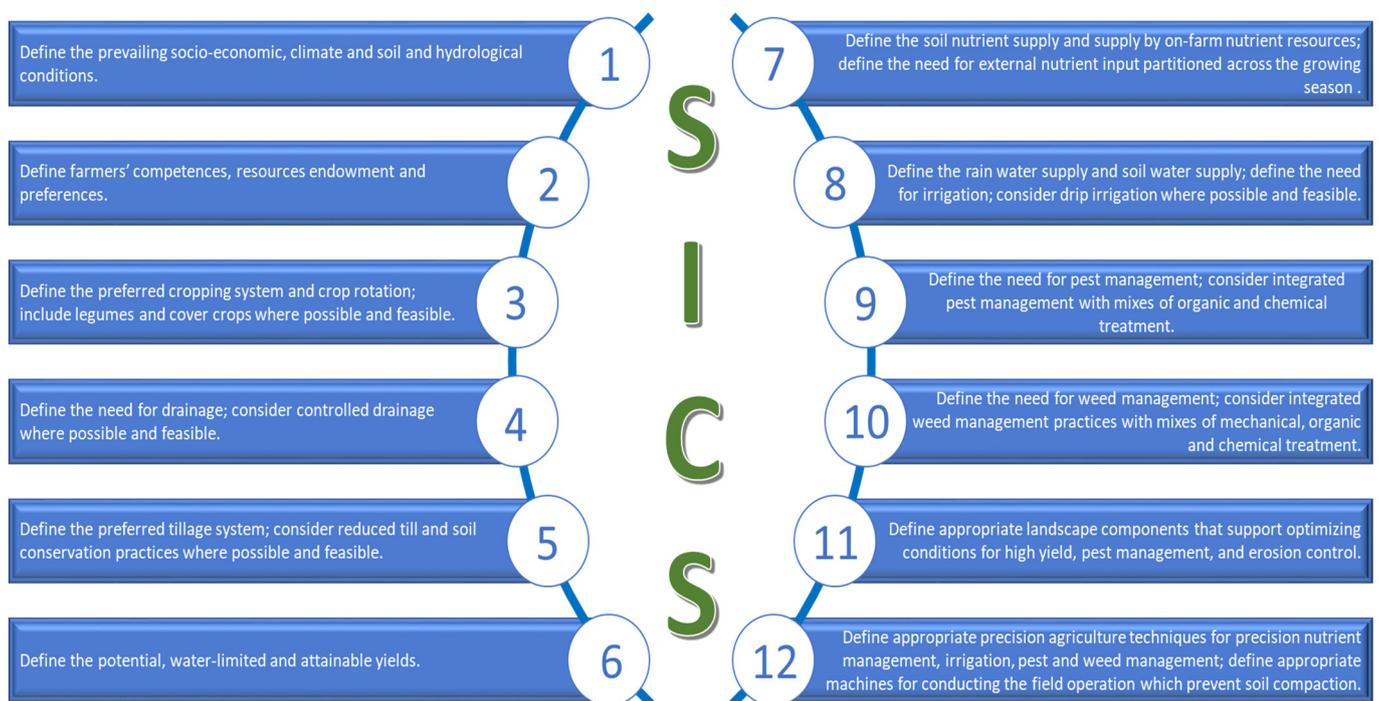


Figure 7. Towards sustainable cropping systems; a step-wise roadmap for developing high-yielding, soil-improving and environmentally sound cropping systems. The steps (1 to 12) have to be taken in a consecutive-iterative manner so as to find the optimal combination of practices.

4.4. Concluding Remarks

Crop husbandry and soil management practices are of critical importance for closing yield gaps, raising farm income and soil quality, and minimizing the environmental impacts of cropping systems in the world. We identified ten categories of crop husbandry and soil management practices, based on the concept of crop yield defining, limiting and reducing factors, and tried to quantify the effects of improved or modified practices relative to conventional practices, by using results of meta-analysis studies.

Our review was based on the premise that meta-analysis papers and reviews synthesize large numbers of experimental studies related to topical research questions and important research findings. For example, closing yield gaps and decreasing environmental impacts are topical, and thus we expected that in the course of the last 20 years when meta-analysis studies blossomed, a wealth of synthesized information would become accessible to help improve crop husbandry and soil management practices and thereby increase crop yield and soil quality, and decrease the environmental impact of crop production. The meta-analysis studies reviewed covered a huge number of experimental studies and practices in different parts of the world, albeit uneven. The number of studies per category

of practices seem to reflect topics of hot societal debates and/or studies with controversial research findings. The number of meta-analysis studies per category of practices seem not to reflect those topics and practices that have largest impacts on crop yields, soil quality, and the environment.

Most meta-analysis studies reported positive effects of specific practices relative to conventional practices, on crop yield, soil quality and the environment. However, most meta-analysis studies examined single practices, with limited emphasis on interactions between categories of practices, and on the optimization across practices. Further, the coverage of studies was uneven, both in terms of practices, sustainability aspects and world regions. Notably, economic aspects were rarely addressed.

Based on this review, we derived a roadmap with twelve steps for integrating and optimization of all main crop husbandry and soil management practices, so as to develop high-yielding, soil-improving, and environmentally-sound cropping systems. We call these ‘soil-improving cropping systems’ to emphasize that cropping systems must maintain and improve soil quality to remain sustainable. This roadmap has been tested in practice and some results are presented in other papers of this special issue. We also made a number of recommendations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land11020255/s1>, Table S1: Cropping: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S2: Nutrient management: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S3: Irrigation and fertigation: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. DI = deficit irrigation, PRD = partial rootzone drying, FI = full irrigation, AI = aerated irrigation, NAI non aerated irrigation, RDI = regulated deficit irrigation, CDI = conventional deficit irrigation, CI = conventional irrigation, OI = over irrigation, UI = under irrigation, OPTI = optimal irrigation. Table S4: Controlled drainage: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest (see Table 1). Table S5: Soil tillage: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. NT = no tillage, TT = traditional tillage, CA = conservation agriculture, RT = reduced tillage, MT = minimum tillage. Table S6: Pest management: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S7: Weed management: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S8: Crop residue management & mulching: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S9: Landscape management: effects on (a) crop yield and quality, (b) soil quality, (c) economic effects, (d) resource use efficiency, (e) environmental effects, and (f) human health impacts as reported in meta analysis studies; aoi = area of interest. Table S10: Explanation of the main columns in the accompanying Excel sheet.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of abbreviations.

Abbreviation	Meaning	Abbreviation	Meaning
abund.	Abundance	N ₂ O	Nitrous oxide (emission)
act.	Activity	NH ₃	Ammonia (emission)
AG activity	Activity of α -1,4-glucosidase	NO ₃	Nitrate (leaching)
AMF	Arbuscular mycorrhizal fungi	NO _x	Nitrogen oxides
aoi	Area of interest	NUE	Nitrogen (nutrient) use efficiency
AWC	Available water content	OA	Organic agriculture
Bact.	Bacteria	OX activity	Oxidative decomposition
BD	Dry bulk density	P	Phosphorus
BG activity	Activity of β -1,4-glucosidase	part.	Particulate
BX activity	Activity of β -1,4-xylosidase	Penetr. R	Penetration resistance
C	Carbon	PEO activity	Peroxidase activity
C-acq. activity	Hydrolytic C acquisition enzymes	PHO activity	Phenol oxidase activity
CBH activity	Activity of β -D-cellobiosidase	PLFA	Phospholipid fatty-acids
CH ₄	Methane	PMN	Potentially mineralizable N
CO ₂	Carbon dioxide emission	PR	Penetration resistance
col.	Colonies	Resp.	Respiration
Dehydrog.	Dehydrogenase activity	richn.	Richness
Dens. herb.	Density herbivorous insects	RO	Runoff
diss.	Dissolved	RR	Response ratio: $RR = (X_t - X_c)/X_c$
div.	Diversity	SDG	Sustainable development goals
Econ. return	Economic return	seq.	Sequestration
EEA	Soil extracellular enzyme activity	SICS	Soil-improving cropping systems
EF	Emission factor	SMB	Soil microbial biomass
EF _{ad}	Additional N ₂ O emission factor [#]	SMC	Soil microbial C
EOC	Extractable organic carbon	SOC	Soil organic C
ET	Evapotranspiration or water use	Soil T	Soil temperature
FNER	Fertilizer N equivalent ratio	SOM	Soil organic matter
GHG	Greenhouse gas	SON	Soil organic N
GWP	Global warming potential ^{\$}	SWA	Soil water-stable aggregate
K	Potassium	TMA	Total microbial activity
Ksat	Hydraulic conductivity at saturation	tot.	Total
LER	Land equivalent ratio	TSS	Total soluble solids
Lrv	Root length density	WP	Water productivity
Max. econ. return	Maximum economic return	WS	Water storage
MBC	Microbial biomass C	WSA	Water stable aggregates
MBN	Microbial biomass N	WUE	Water use efficiency
MWD	Aggregate mean weight diameter	Xc	Effect (value) of control treatment
N	Nitrogen	Xt	Effect (value) of specific treatment

[#]: which is the conservation tillage-induced change in N₂O emission compared to conventional tillage when N fertilizer is applied; ^{\$}: CH₄ and N₂O emissions per unit yield.

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