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Review

Soil Compaction Prevention, Amelioration and Alleviation Measures Are Effective in Mechanized and Smallholder Agriculture: A Meta-Analysis

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Abstract: Background: The compaction of subsoils in agriculture is a threat to soil functioning. Measures aimed at the prevention, amelioration, and/or impact alleviation of compacted subsoils have been studied for more than a century, but less in smallholder agriculture. Methods: A meta-analysis was conducted to quantitatively examine the effects of the prevention, amelioration, and impact alleviation measures in mechanized and small-holder agriculture countries, using studies published during 2000~2019/2020. Results: Mean effect sizes of crop yields were large for controlled traffic (+34%) and irrigation (+51%), modest for subsoiling, deep ploughing, and residue return (+10%), and negative for no-tillage (−6%). Mean effect sizes of soil bulk density were small (<10%), suggesting bulk density is not a sensitive 'state' indicator. Mean effect sizes of penetration resistance were relatively large, with large variations. Controlled traffic had a larger effect in small-holder farming than mechanized agriculture. Conclusion: We found no fundamental differences between mechanized and smallholder agriculture in the mean effect sizes of the prevention, amelioration, and impact alleviation measures. Measures that prevent soil compaction are commonly preferred, but amelioration and alleviation are often equally needed and effective, depending on site-specific conditions. A toolbox of soil compaction prevention, amelioration, and alleviation measures is needed, for both mechanized and smallholder agriculture.

Keywords: compacted subsoils; crop yield; mechanized agriculture; smallholder agriculture; soil bulk density; soil penetration resistance; tillage

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1. Introduction

Soil compaction is defined as the 'densification of soil and the distortion of soil structure', which cause the deterioration or loss of one or more soil functions [1,2]. Compacted soils have a relatively high soil bulk density and soil strength, a low number of macro pores, and a relatively high tortuosity, and thereby a low hydraulic conductivity and water infiltration rate [3,4]. These phenomena increase the risks of temporal water logging, runoff, and erosion [5]. Compacted soils impede root elongation and development, and thereby limit soil nutrient uptake and crop development, which in turn causes yield loss [6,7]. The altered soil aeration and wetness and the decreased root growth and crop production also affect soil biodiversity and biological activity, and thereby nutrient transformations and greenhouse gas emissions [4]. Decreased aeration and increased wetness may also predispose compacted soils to infection of root rot diseases [8]. Compacted soils are widespread and have been recognized as a global threat for modern agriculture [9,10]. Greatest concerns relate to subsoil compaction, because of the difficulty to ameliorate subsoil compaction [11,12].

Compacted soils are not easily recognized. This relates especially to compacted subsoils. There are various measures to assess subsoil compaction, e.g., [3], but there is little routine monitoring of soil compaction in practice. Yet, the concerns for soil compaction in the scientific literature is steadily increasing (Figure S1). This increased attention is especially related to the impacts of the increasing mechanization and wheel loads of machines in agriculture [13]. It was noted that a significant fraction of arable farmers in Germany are aware of the risk of intensive field traffic and high axle loads for subsoil compaction, but that this awareness had not yet led to adequate changes in practice [14]. Indeed, the impacts of human-induced (sub)soil compaction seem to increase over time [10,15,16].

Next to human induced soil compaction, through trafficking and ploughing (forming traffic and plough pans in the subsoil), soils may become compacted through natural processes, e.g., during peri-glacial conditions, or as a result of the illuviation of soil colloids, cracking and swelling processes (combined with topsoil tumbling down to the subsoil when cracks are open), heavy rains, and soil trampling by animals. Soils may have a compacted subsoil also because of an abrupt textural or mineralogical change with depth, due to a different geo-genetic origin [3]. The susceptibility of soils to compaction differs greatly. Most susceptible are soils with low soil organic matter content and a high content of silt (particles with a size of 20 to 50 μm). These soils often have a low structural stability and may be characterized as 'sealing, crusting, and hardsetting' [8,17].

Measures to ameliorate compacted subsoils and/or to alleviate their impacts have been explored almost as long as the problem has been realized [18,19]. Hence, many studies have examined the effectiveness of amelioration and alleviation measures, including deep tillage, subsoiling, reduced tillage, crop rotation, reduced trafficking, and using soil amendments. Results of these studies have been discussed and summarized in some excellent reviews. For example, Ungar and Kaspar [6] reviewed studies examining root growth in compacted soils and suggested that tillage and growing deep-rooted crops in rotations will help avoid subsoil compaction and alleviate negative impacts. Soane and Van Ouwerkerk [20] summarized the early studies related to the nature and alleviation of soil compaction. While reviewing the literature since the early 1990s, Hamza and Anderson [21] identified eight practices to avoid, delay, or prevent soil compaction, and suggested that specific combinations of measures are most effective. The review of Batey [3] largely confirmed the suggestions of Hamza and Anderson [21] and emphasized the need for the monitoring of soil compaction in practice. Nawaz et al. [4] reviewed models simulating soil compaction and the effects of soil compaction, while Chamen et al. [22] reviewed studies examining the costs and benefits of measures aimed at ameliorating soil compaction. Schneider et al. [23] quantitatively examined the effects of deep tillage on crop yield, using a meta-analysis of data mainly from Europe and North America, and observed that deep tillage effects were highly site-specific. Shaheb et al. [7] reviewed how soil compaction affected different crop types and listed twelve management strategies to alleviate soil compaction. Most studies focused on mechanized agriculture and paid little attention to smallholder agriculture. Of a different nature, Kodikara et al. [24] reviewed how soil compaction can be improved in civil engineering and transport.

Evidently, soil compaction is a complex and persistent phenomenon affecting the sustainability of crop production in modern agriculture in large areas of the world. The threat of subsoil compaction for crop production is thought to be most severe in mechanized agriculture with high axle loads on wet soils [2,12,25,26]. However, there are also reports on subsoil compaction in smallholder agriculture in China, for example, as a result of long-term soil cultivation practices, irrigation, and natural conditions [27]. It is unclear whether the effects of amelioration and alleviation measures are different between mechanized and smallholder agriculture. Machine weight is much less and ploughing depth is also less in smallholder agriculture than in mechanized agriculture. We hypothesized that amelioration and alleviation measures are more effective in smallholder agriculture than in highly mechanized agriculture, because compacted soil layers are likely more shallow in smallholder agriculture, and thus easier to remediate.

We conducted a systematic review of the quantitative effects of measures aimed at preventing and ameliorating compacted subsoils or at alleviating the impacts of soil compaction on crop yield and soil physical properties, using a meta-analysis of published studies conducted in areas with smallholder farms (mainly China), and in mechanized agriculture in Europe, America, and Australia. We categorized measures in three groups (Table S1), largely following Hamza and Anderson [21] and Chamen et al. [22]: (i) measures aimed at avoiding and preventing subsoil compaction, including minimized and controlled trafficking, zero and minimum tillage (rotary tillage and shallow harrowing); (ii) measures aimed at remediating compacted subsoils, including subsoiling, deep ploughing, and crop rotation; and (iii) measures aimed at alleviating the effects of compacted subsoils, including residue return, controlled irrigation, and manure application. This categorization of measures also fits in the DPSIR framework[1] [2].

The objectives of our study were (1) to quantitatively examine the effects of measures aimed at avoiding and ameliorating soil compaction and at alleviating the impacts of compacted subsoils on crop yield, soil bulk density, and soil penetration resistance, using results of published studies; and (2) to examine the effectiveness of measures in smallholder and mechanized agriculture. We focused on the period 2000–2019/2020, because of the existence of some excellent reviews covering the earlier period, and because studies on smallholder agriculture conducted before 2000 are relatively scarce.

2. Materials and Methods

2.1. Data Collection and Screening

We searched for peer-reviewed publications investigating the effectiveness of measures to address compacted (sub)soils, using Web of Science and China Knowledge Resource Integrated Database (CNKI, for Chinese studies not published in English language). Search terms were ("soil compaction" OR "compacted soil" OR "compacted subsoil" OR "subsoil compaction") AND ("yield" OR "biomass") AND ("density" OR "penetration" OR "soil cone index") in titles, keywords, and abstracts. In Web of Science, conference proceedings and non-English publications were excluded. This search gave 719 publications published between 2000 and 2019 (until 1 August 2019). The search in the China Knowledge Resource Integrated Database yielded 74 additional publications (from 2000 to August 2019).

The search process was followed by a screening procedure that was based on the following criteria: (1) field studies must include side by side comparisons of soil compaction prevention, remediation and/or alleviation treatments, and control (or reference) treatments; (2) for each paired comparison, treatments and reference treatments have the same location, cropping system, cropping management, and year; (3) grain yields and/or biomass yields were reported; (4) soil bulk density and/or soil penetration index data were reported; (5) the test crops were cereals, including wheat, maize, barley, oat, and sorghum; (6) location(s), year(s), and basic soil information of the experiment(s) were stated. Only studies with cereal crops as test crops were included. One reason for this is the importance of cereal crops in global food supply [28], and the other reason is that the results are likely more robust when using crops with similar root morphology and physiology [7]. Grain yield and/or biomass yield were used as crop response indicators.

Following the aforementioned screening procedure, we obtained 400 comparisons (paired observations) of crop yields from 54 studies in 28 countries from Web of Science, and 157 comparisons of crop yields from 23 studies from CNKI. Treatment measures were recorded and grouped. THe results of crop yield and soil bulk density/penetration resistance were extracted from each study, as well as characteristics related to location, experimental year(s), and soil clay content (Table S1). In cases where crop yield and/or soil bulk density and/or penetration results were presented in figures only, values were extracted using the GetData Graph Digitizer (https://apps.automeris.io/wpd/ (accessed on 1 January 2020)).

2.2. Categorization of the Measures

The paired observations were allocated to a category of measures, i.e., prevention, remediation, or alleviation measures. There is some degree of arbitrariness in the allocation of measures. For example, the choice of crop type and crop rotation was categorized as remediation measure but could have been categorized as prevention or alleviation measures equally well. Further, alleviation measures were thought to alleviate the effects of soil compaction, but may contribute also to remediation or prevention, depending on the environmental and management conditions. Thus, irrigation, fertilization, manure application, and straw return were thought to alleviate the impacts of compacted subsoils on root growth (their limited ability to take up water and nutrients from compacted subsoils).

Conventional (random) traffic was chosen as reference treatment for controlled traffic. In this case, a comparison was made between random (deliberate) trafficking and minimal or controlled trafficking, to infer the effects of controlled trafficking indirectly. Thus, random trafficking was used as reference treatment (worst-case), while minimal trafficking or controlled trafficking as the remediation treatment. The reference treatment of manure application was no manure application, while residue return was compared to no residue return. Crop rotation effects were compared to effects of mono-cropping.

Soil bulk density and soil penetration resistance results were grouped into three depth intervals: 0–20 cm (topsoil), 20–40 cm (upper subsoil), and 40–60 cm (lower subsoil). This grouping was seen as a compromise for comparing smallholder and mechanized agriculture. The depth of soil cultivation in smallholder agriculture is commonly less than 20 cm but in mechanized agriculture often a bit deeper, depending also on tillage system. Moreover, about 80% of the roots of most cereal crops are in the upper 40 cm and more than 95% of the roots are in the upper 60 cm of the soil [29,30].

Smallholder farms are mostly found in east and south Asia, Africa, and some countries of Latin America [31], and mechanized agriculture with relatively high axle loads in North America, Oceania, Europe, and west Asia. Therefore, studies conducted in south and east Asia and Africa were considered to be small-holder farming, while studies conducted in America, Europe, Australia, and west Asia were considered to be in mechanized agriculture. For more detailed information of the database composition, see Tables S1 and S2.

2.3. Data Analysis

Our meta-analysis basically followed the same approach as the one described by Qin et al. [32]. We used the natural logarithm of the ratio of the response variable of two treatments as the effect size [33]: $\ln(R) = \ln(x_t/x_c)$, where R is the ratio, x is the response variable, and subscripts t and c refer to the specific treatment and control treatment. The response variable was either crop yield (x = Y), dry bulk density (x = BD), or penetration resistance (x = PR).

For the calculation of a grouped effect size, a linear mixed-effect model was used for which we used the R-package 'nlme' [34]. Mixed-effect models are preferred to fixed-effect models for statistical testing in ecological data synthesis because their assumption of variance heterogeneity is more likely to be satisfied [33]. In our study, results of treatments addressing soil compaction were set as fixed effects and study numbers were set as random effects, to allow accounting for variances among studies. We used the equal weighting method (e.g., [35]) when comparing studies with different number of replicates. The ln(R) of the individual pairwise comparison was used as the dependent variable. The mean effect size and the 95% confidence intervals (CIs) of each categorical group were estimated. The significance of the effects was statistically assessed at the 0.05 confidence level. In the graphs (forest plots), the effect-size of each treatment was transformed back and converted to a percentage change in crop yield, dry bulk density, or penetration resistance relative to the control or reference treatment, i.e., data were presented as $(R - 1)*100\%$. In case the value zero in such a forest plot falls outside the 95% CI, the given average value (effect size) is assumed to be significantly different from zero.

3. Results

3.1. Overview of the Dataset

Our dataset consisted of 557 yield comparisons, 620 soil bulk density comparisons, and 592 soil penetration resistance comparisons. About half of the number of bulk density comparisons dealt with the topsoil (346), and half with the subsoil (274). More yield comparisons were from countries with predominantly small-holder farming (S-farming) (323) than from countries with predominantly mechanized agriculture (M-agriculture) (234). More yield observations were related to prevention (221) and remediation measures (205) than alleviation measures (131, Figure 1a). Yield observations of prevention measures were found more in M-agriculture countries than in S-farming countries. The number of yield observations related to remediation and alleviation measures was two times larger with S-farming than M-agriculture (Figure 1b,c).

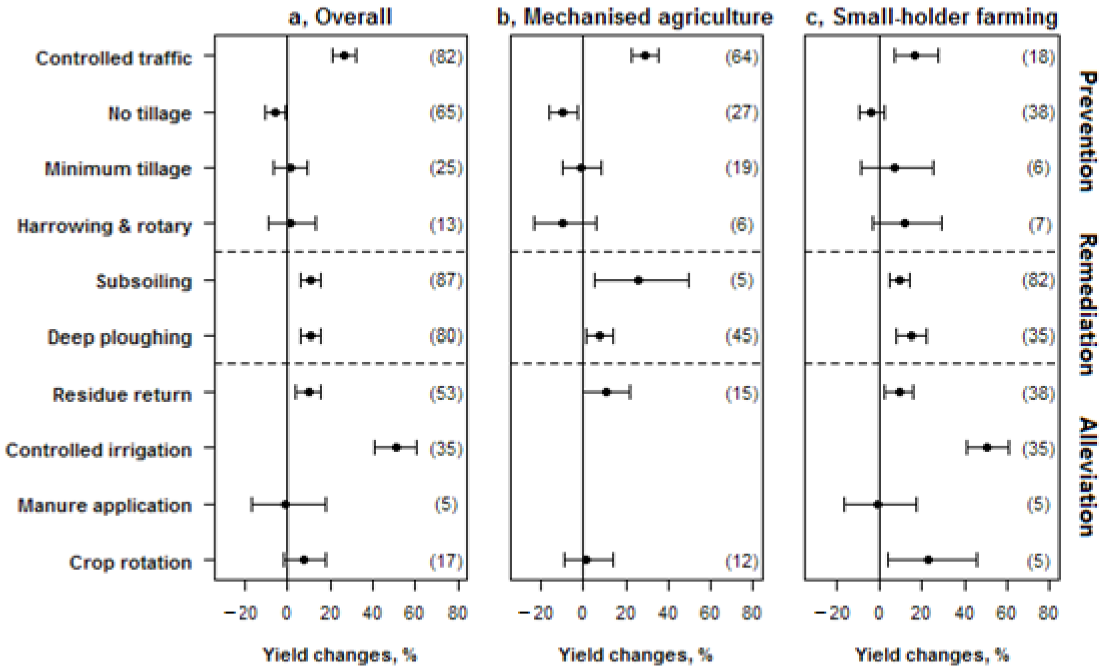

Figure 1. Relative changes in crop yield (%) in response to soil compaction prevention, remediation and alleviation measures; means of all results (**a**); means of results from countries with mechanized agriculture (**b**); means of results from countries with small-holder farming (**c**). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.

3.2. Effects of Measures on Crop Yields

Five out of ten measures examined had positive effects on crop yields, including prevention, remediation, and alleviation measures ($p < 0.05$, Figure 1a). Relatively large mean effect sizes were noted for controlled traffic (+26%) and irrigation (+51%). Mean effect sizes were also significantly positive for subsoiling, deep ploughing, residue return, and crop rotation (+8% to +11%). Minimum tillage and manure application did not display significant effects, while no tillage had a negative mean effect on crop yield (−6%).

Differences between S-farming and M-agriculture in the mean effect sizes of prevention, remediation, and alleviation measures on crop yields were relatively small (Figure 1b,c). The mean effect size of controlled traffic on crop yield was two time higher in M-agriculture (+38%) than in S-farming (+16%). However, the number of comparisons was much larger in M-agriculture (88) than in S-farming (21). Subsoiling was more studied in S-farming than in M-agriculture during the last 20 years and the mean effect on crop yield in S-farming was positive (+8%). Controlled irrigation and manure application were examined in S-farming but not in M-agriculture as possible measures to alleviate the effects of compacted subsoils.

Evidently, controlled irrigation had a large effect size, but it is not realistic to ascribe this effect merely to the alleviation of soil compaction. Likely, crop yields in the reference treatments were limited by drought and not only by compacted subsoils.

3.3. Effects of Measures on Soil Bulk Density

The measures had a relatively small effect on the soil bulk density of the top soil and subsoil (Figure 2a,d), compared to their effects on crop yields (Figure 1). Relative mean changes in bulk density were in the range of 0–9%. For the subsoil, which is most critical, controlled traffic, deep ploughing, subsoiling, residue return, and crop rotation decreased soil bulk density by on average 2–9% ($p < 0.05$; Figure 2d). Controlled irrigation increased bulk density in the topsoil and subsoil, while minimum tillage increased subsoil bulk density by 3% ($p < 0.05$; Figure 2d).

Essentially all comparisons related to the effects of subsoiling and deep ploughing on subsoil bulk density originated from S-farming. As a consequence, no proper comparison can be made between S-farming and M-agriculture on the effects of subsoiling and deep ploughing. This holds for alleviation measures as well. Controlled trafficking decreased soil bulk density in both topsoil and subsoil, and S-farming and M-agriculture.

3.4. Effects of Measures on Soil Penetration Resistance

Soil penetration resistance responded to the measures in a similar way as bulk density, but the relative changes were larger (Figure 3a,d). Controlled traffic treatments had on average 33% lower penetration resistance in topsoils and 26% lower resistance in subsoils than the reference treatments. Subsoiling and deep ploughing decreased penetration resistance by 13% to 20% ($p < 0.05$, Figure 3d). No tillage increased penetration resistance in the topsoil but not in the subsoil.

Observations on subsoiling and deep ploughing originated mainly from S-farming countries, where these measures decreased penetration resistance. Residue return decreased penetration resistance in both topsoil and subsoil in S-farming. The number of comparisons for residue return was too low in M-agriculture to make firm statements. Irrigation slightly decreased penetration resistance in the topsoil but not in the subsoil in S-farming.

3.5. Effects of Experimental Duration

More than 80% of the comparisons dealt with short-term experiments (1~3 years; Table S1). Tillage treatments (deep ploughing, subsoiling, no tillage, minimum tillage) accounted for almost half (47%) of the long-term experiments (≥4 years), followed by controlled traffic (23%). For controlled traffic, the relative effect size for crop yield and for subsoil bulk density tended to increase over time (Figure 4a). For crop yield, the effect size was 33% in short-term and 37% in long-term experiments, while subsoil bulk density was 4% lower in short-term and 6% lower in long-term experiments compared to the reference treatments ($p< 0.05$; Figure 4b,c). For deep ploughing, the relative effect size for crop yield and bulk density decreased over time. In short-term (1~3 yrs) experiments, mean effect sizes were statistically significant on crop yields and bulk density ($p < 0.05$), but not in long-term (≥4 yrs) experiments. Similar results were found for no tillage (Figure 4).

3.6. Effects of Soil Texture

Soil texture (silt and clay contents) and soil organic matter content affect the susceptibility of soils to compaction and also likely influence the effect sizes of measures. A clay content of 17.5% is commonly used as a threshold value in soil compaction evaluation. Soils with <17.5% clay are considered to be more susceptible to compaction than soils with ≥17.5% clay [36]. Thus, we compared the effect sizes of measures for soils with <17.5% clay with soils having ≥17.5% clay. Yield effects were on average similar for the two textural classes (Figure 5). However, light-textured soils (<17.5% clay) showed greater responses to prevention and amelioration measures than heavy-textured soils (≥17.5% clay). This was most notable for controlled traffic. Effect sizes for yield differed by more than a factor two

(+49% vs. +19%; $p < 0.05$), for subsoiling (+12% vs. 3%), and deep ploughing (13% vs. 8%; $p < 0.05$).

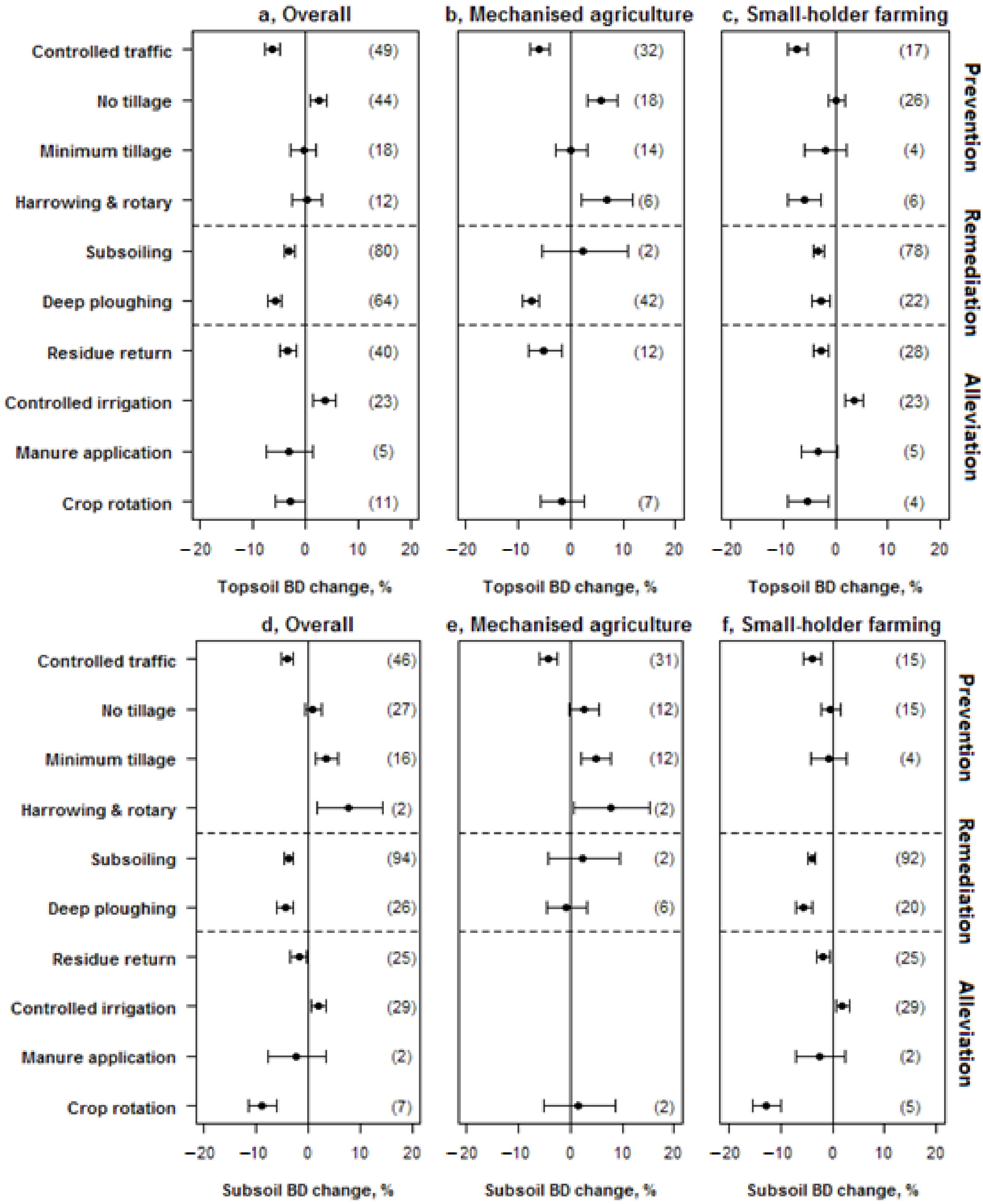

Figure 2. Relative changes in soil bulk density (BD) in response to soil compaction prevention, remediation and alleviation measures for the topsoil (**a**–**c**) and for the subsoil (**d**–**f**); means of all results (**a**,**d**); means of results from M-agriculture (**b**,**e**); means of results from S-farming (**c**,**f**). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.

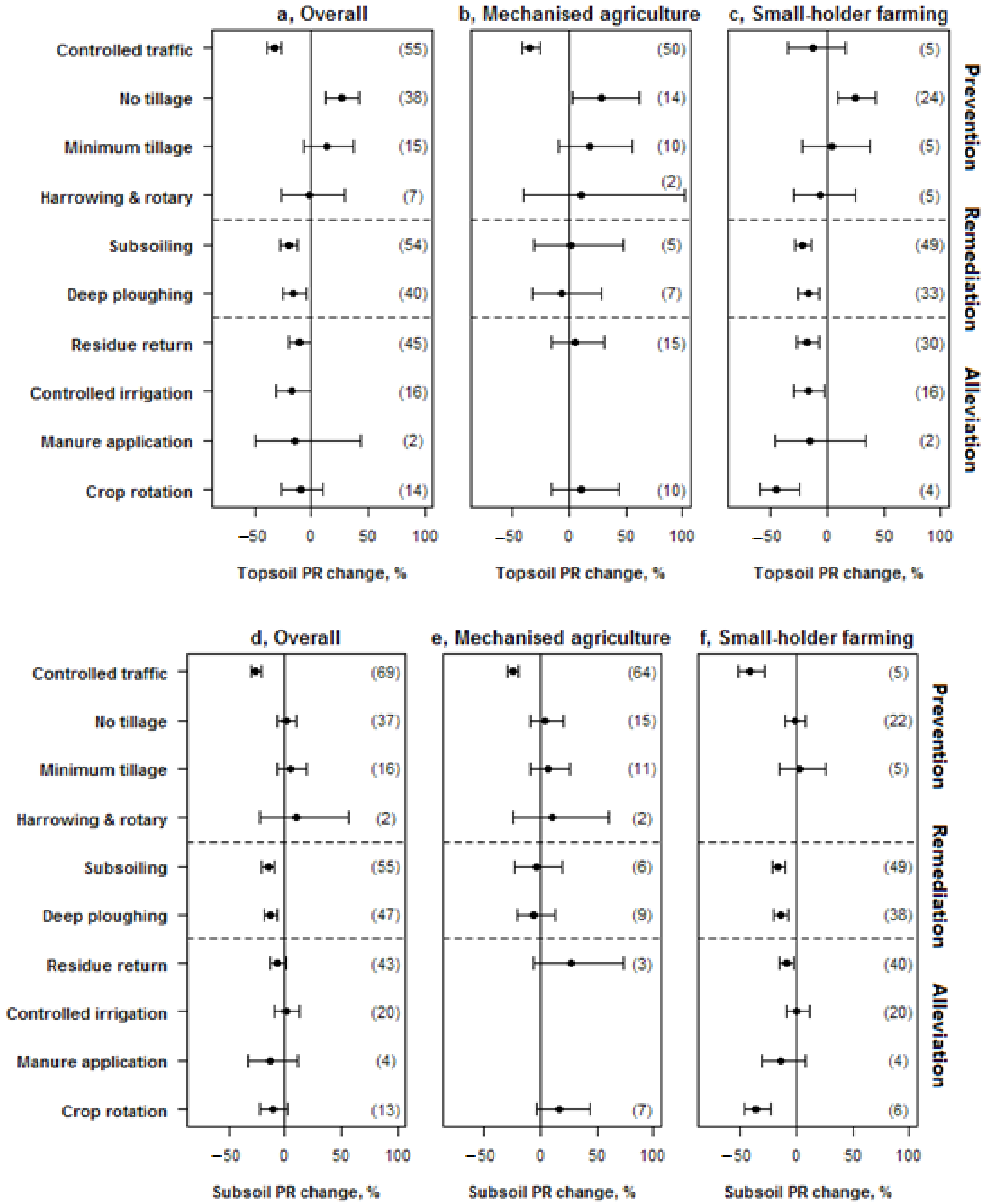

Figure 3. Relative changes in soil penetration resistance (PR) in response to soil compaction prevention, remediation and alleviation measures for the topsoil (**a**–**c**) and for the subsoil (**d**–**f**); means of all results (**a**,**d**); means of results from M-agriculture (**b**,**e**); means of results from S-farming (**c**,**f**). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.

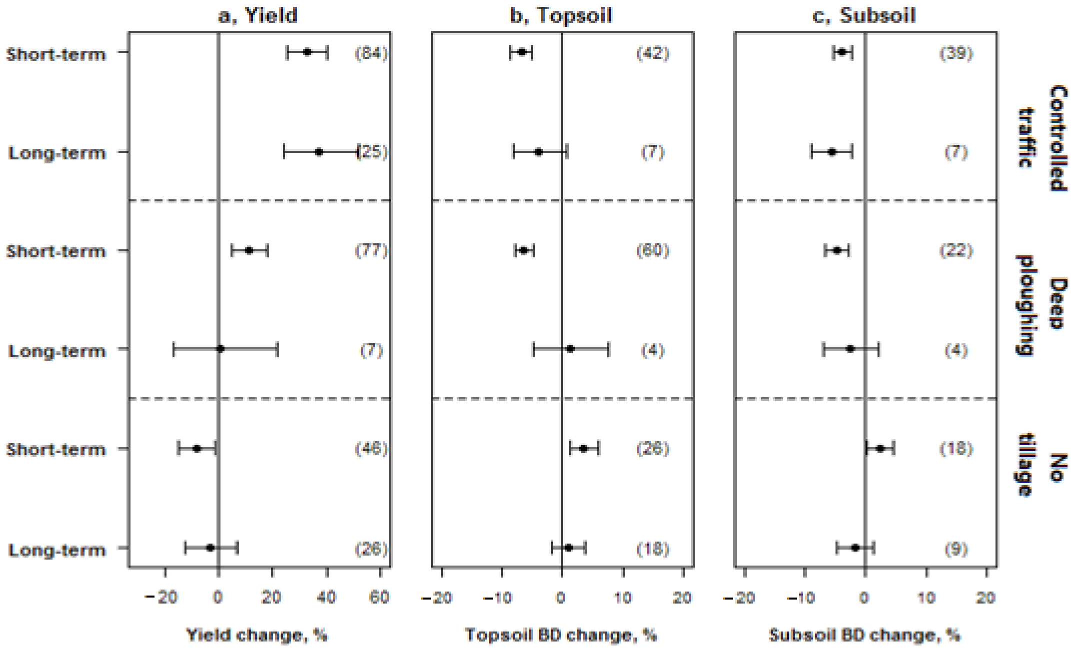

Figure 4. Relative changes in crop yield (**a**) and soil bulk density (BD; for top soil, (**b**); and subsoil, (**c**)) in response to various soil compaction prevention, remediation and alleviation measures; means and standard deviations of results from short-term (<4 years), and long-term (≥4 years) field experiments.

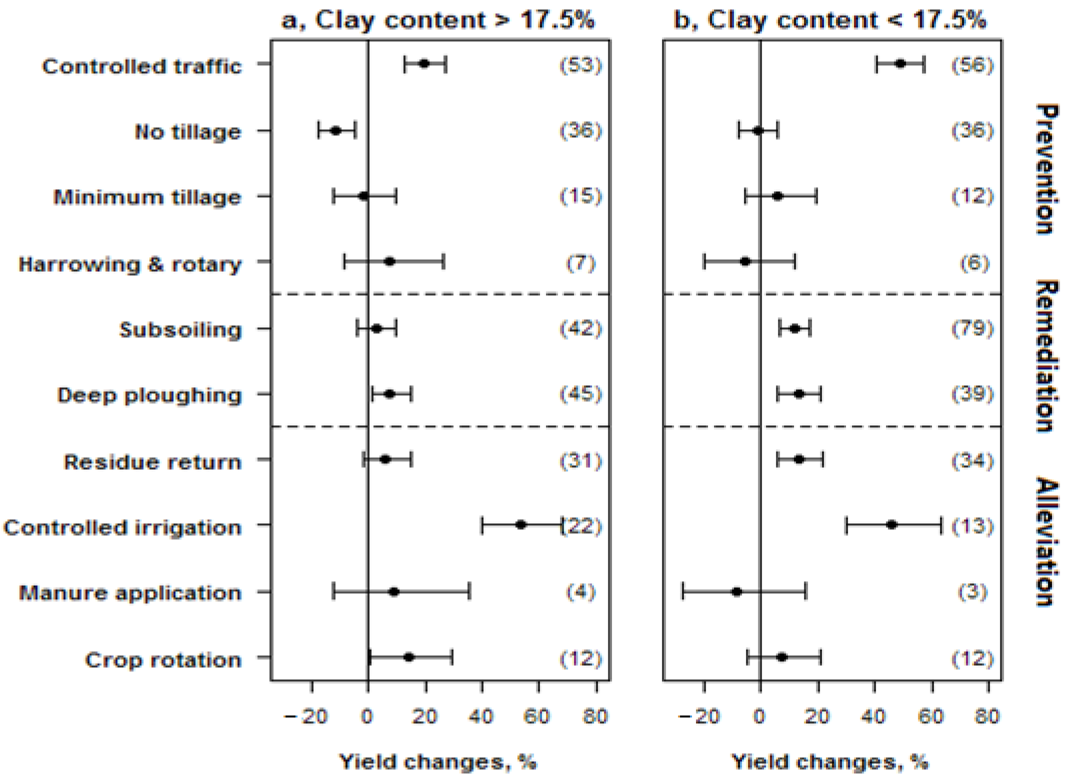

Figure 5. Relative changes in crop yield (%) in response to soil compaction prevention, remediation and alleviation measures; means of results from clay soil (clay content ≥17.5%) (**a**); means of results from sandy soil (clay content < 17.5%) (**b**). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.

4. Discussion

4.1. Understanding the Cause-Effect Relationships

The cause–effect relationships of soil compaction and its mitigation measures can be analyzed and understood through the 'driving forces, pressures, state, impact, responses' (DPSIR) framework [2]. In agriculture, the driving forces often stem from the economic incentives to produce more and to lower costs, especially in affluent countries [11,13]. This leads to more intensive soil cultivation and the use of larger and heavier machines, which exerts literally pressure on the soil. This pressure may lead to a densification of the (sub)soil, i.e., compacted (sub)soils, with impacts on water infiltration, root and crop growth, microbiological processes, and gaseous emissions, e.g., [3]. The response of farmers and land managers may be directed towards avoiding or preventing soil compaction, i.e., addressing the driving forces and pressures, or they may focus on the amelioration of compacted soils, i.e., addressing the state, or at alleviating the impacts of compacted soils, or both (Figure 6). Thus, the three categories of measures distinguished in our meta-analysis (Table S2; Figure 1) address different aspects of the cause–effect chain of soil compaction.

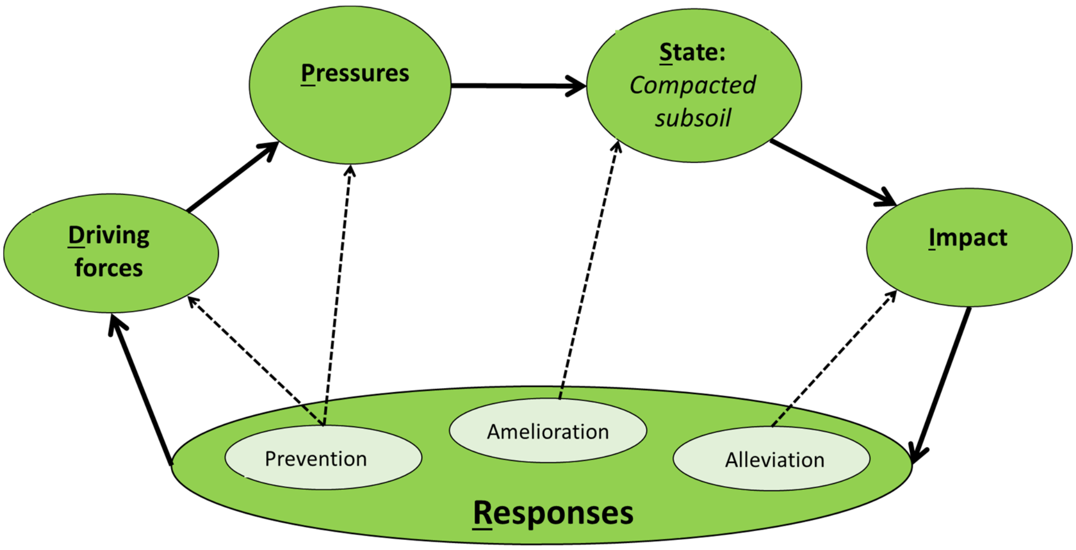

Figure 6. The Driver-Pressure-State-Impact-Response (DPSIR) concept with focus on soil compaction. The response measures indicate which part of the DPSIR chain is being addressed by the measures.

Avoiding, preventing, and precautionary strategies are preferred above amelioration and alleviation strategies, also because of the complexities and imperfections of the latter [2,37]. However, large areas in the world have naturally compacted subsoils (e.g., [8,17]), or have been compacted by human activities in the past [15], and thus will need amelioration and alleviation strategies. Moreover, the susceptibility of soils to densification and the farming and environmental conditions greatly differ across the world, suggesting that region- and farm-specific strategies will be needed, and thus a toolbox of options and strategies. Our meta-analysis contributes to this toolbox by examining quantitatively the effects of both prevention, amelioration, and alleviation measures.

Depending on the strategy, different indicators may be used for evaluating the effectiveness of the strategy. Lebert et al. [37] discussed indicators for precautions against soil compaction (pressure indicators) and for the impairment of subsoil structure through compaction (state indicators). For the first, they proposed the 'pre-compression stress' and 'loading ratio', which can be calculated for different soils, but need soil type specific calibration [37]. For assessing the impairment of subsoil structure, they proposed three indicators, i.e., air capacity (>5% air filled porosity at a water suction of pF 1.8), saturated water conductivity (<10 cm day^{-1}), and a visual classification of the soil morphology (combination of a 'spade diagnosis' and measurements of the effective bulk density and packing density). The second suggested indicator (saturated water conductivity) is basically an impact indicator (and not a state indicator). Soil bulk density was not recommended as an indicator for identification of 'harmful' soil compaction, because 'there is no critical threshold and classification scheme' according to the authors [37]. However, for the related 'packing density' (bulk density corrected for clay content) indicator, there are criteria [38]. Håkansson and Lipiec [39,40] reviewed the usefulness of the relative soil bulk density, or the degree of compactness, which was defined as the dry bulk density in percent of a reference dry bulk density of the same soil obtained by a standardized, long-term, uni-axial compression test at a stress of 200 kPa. Evidently, the measurements of the state of soil compaction are labor-intensive, and thus costly, especially when considering spatial within-field variations [41,42]. As a result, routine monitoring of the state of soil compaction in farmers' fields is not common practice. Indeed, it appears costly and there is debate about appropriate indicators and their interpretation. We observed that soil bulk density and penetration resistance are most commonly used as indicators for assessing the state of soil compaction in field experiments to test measures aimed at preventing, ameliorating, and/or alleviating soil compaction. However, bulk density is not a sensitive indicator (e.g., relative changes in soil bulk density following the implementation of measures are relatively small; Figure 2), while penetration resistance is very sensitive to variations and changes in soil moisture content. Based on uni-axial tests, Panayiotopoulos et al. [43] showed that for a compression stress up to 300 kPa the dry bulk density changed up to 5~15%. This suggests that extreme changes in dry bulk density are not likely to occur. Further, measurements of penetration resistance should be performed at pressure heads of about −100 cm. It is, however, unlikely that this was the case in all studies. This may explain why a large variability in penetration resistance was found in the reviewed studies.

Impact indicators relate to the changes in soil ecosystem functioning following a change in the densification of the soil and associated changes in pore size distributions, tortuosity, and soil structure. Possible impact indicators are crop yield, hydraulic conductivity, run-off and ponding, and emissions of CO_2, CH_4, and N_2O [3,44]. There are no critical thresholds and classification schemes for assessing changes in soil functions, perhaps apart from hydraulic conductivity [37]. Yet, comparisons can be made between situations without and with compacted (sub)soils as in our meta-analysis. Crop yield is probably the most powerful indicator in farmers' practice, because of its influence on farm income, although part of a yield penalty may be nullified through alleviation measures, including irrigation and fertilization.

In conclusion, the DPSIR framework is useful for analyzing and understanding the cause–effect relationship of soil compaction, but further work is needed to derive a proper set of indicators and threshold values.

4.2. Impacts of Measures in Small-Holder Farming and Mechanized Agriculture

The mean effect of controlled traffic on crop yield was 38% (range 32–45%) in mechanized agriculture (M-agriculture) and 16% (range 6–27%) in small-holder farming (S-farming). The wide range of yield effects is roughly in the same range as reported by Antille et al. [16] in a review of 20 studies for various crops. The yield of crops was 0–98% higher when grown in the absence of field traffic compared to the yield of crops grown under typical traffic intensities. Controlled traffic was introduced in commercial-scale farming in the 1990s, initially in Australia and subsequently in Europe and northern America [45,46]. The net economic benefit of controlled traffic increases with farm area. Conversely, the yield effect of controlled traffic needs to be relatively large to make controlled traffic economically attractive in small farms [16,22]. It is therefore no surprise that the number of experimental studies was much larger in M-agriculture than S-farming (Figure 1b,c). Interestingly, the mean yield effect of controlled traffic was on average a factor of two smaller in S-farming than in M-agriculture, which may indeed reflect differences in axel loads between S-farming and M-agriculture.

Zero-tillage minimizes the traffic of soil-cultivating tractors and was therefore considered to be a preventive measure for soil compaction, but it does not necessarily control the traffic of other (e.g., harvesting) machines in the field. There is a lot of interest in zero-tillage and minimum tillage (e.g., [47], as it saves labor and fuel cost, minimizes erosion (especially when combined with surface mulching), and contributes to enhanced soil carbon sequestration. However, it increases N_2O emissions and decreases crop yield. The latter is in agreement with our findings (Figure 1). Further, it tends to increase the soil bulk density and penetration resistance of the topsoil (Figures 2 and 3). The no-till (or reduced-till) compacted topsoils limit root penetration and plant growth [48], while crop residues remaining on the soil surface may increase the incidence of viruses and plant pathogens [49], and lower the soil temperature [50,51]. Our study indicates that current zero-tillage and minimum tillage practices are much less effective as a preventive measure for soil compaction than controlled traffic. However, there is a need for more soil physical and soil structural measurements (including bulk density) of the subsoil in no-till systems to confirm our findings.

Deep ploughing and subsoiling increased crop yields by on average 10% and 9%, respectively, though with relatively large uncertainty bars (Figure 1a). These mean effects were derived mainly from studies conducted in S-farming and reported between 2000 and 2019/2020. Schneider et al. [23] reported rather similar mean positive effects of deep tillage on crop yield (6%), based on a meta-analysis of 45 studies (67 field experiments) that were mainly conducted in Europe and North America between 1918 and 2014 (only three studies were reported after 2000, namely one from North America, one from Argentina, and one from China). They noted that the popularity of deep tillage decreased from the 1970s. Peralta et al. [52] also found positive mean effects of subsoiling on the yield of maize (+6%) and soybean (+26%) in no-till systems in Argentina, using a meta-analysis of 32 field studies. Our study indicates that positive effects of deep tillage on crop yields also hold for smallholder farming, notably China, for both deep tillage and subsoiling. Schneider et al. [23] found that the mean effect size of deep tillage on crop yield depended on the silt content of the topsoil, the density of the subsoil, and drought, but not on the deep tillage method (subsoiling vs. deep ploughing and deep mixing) and tillage depths. The strong interference by drought agrees with our observation that irrigation alleviates the effects of compacted subsoils and greatly increases crop yield (Figure 1). The effect of deep ploughing on crop yield decreased over time (Figure 4). A similar trend was observed in the meta-analysis studies of Schneider et al. [23] and Peralta et al. [52]. The decreasing effect of deep tillage over time is likely the result of re-compaction [22,53]. Our analyses indicate that deep tillage decreased soil bulk density (Figure 2) and penetration resistance (Figure 3) of the topsoil and subsoil. Similar decreases were noted for the topsoil by Peralta et al. [52], but neither Peralta et al. [52] nor Schneider et al. [23] reported changes in soil bulk density and/or penetration resistance for the subsoil in response to deep tillage.

Alleviation measures mainly aim to lessen the negative impacts of compacted subsoils on root and crop growth. Roots elongate less in compacted and dry soils due to a combination of mechanical impedance and water stress [54], and thereby have less access to soil moisture and nutrients. Irrigation thus greatly alleviates the negative impacts of compacted subsoils on crop yield. The mean effect size of irrigation on crop yield was 50% (Figure 1). However, irrigation increased soil bulk density in the topsoil and subsoil (Figure 2). These results are based on observations in S-farming countries only, i.e., mainly China. Crop residue return or surface mulching also had a positive on crop yield, likely because of its effect on soil water preservation [32]. Crop residue return decreased soil bulk density (Figure 2), possibly as a result of enhanced soil carbon sequestration [47]. Only a few studies explicitly examined the effects of manure application on alleviating impacts of compacted subsoils on crop yield. No significant effects on crop yields were found, but manure application in S-farming tended to decrease soil bulk density, possiblY through enhancing soil organic carbon contents [55,56]. In summary, alleviation measures 'treat the symptoms but not the root cause', yet some of these measures can be highly effective, also in cases where amelioration measures were not much effective.

4.3. Managing Soil Compaction

A common opinion is that 'the best way to manage soil compaction is to prevent it from happening'. The popularity of controlled traffic and reduced or no till practices reflects this opinion. The increasing wheel loads and weight of agricultural machinery in practice in especially Europe and North America during the last 60 years do not reflect this opinion. The increase in machinery weight has resulted in an increase in subsoil compaction, which may have contributed to crop yield stagnation and to an increase in the incidence of flooding in Europe [13]. The cascade of possible impacts from soil compaction beyond field and farm scales (e.g., increased risk of flooding, runoff, and erosion) could be seen as driver for actions by policy [57,58]. However, soil compaction is not subject to a coherent set of rules in, for example, the European Union (EU), and is also not mentioned in the recent EU soil strategy for 2030 [59]. Thus, farmers depend on the insights and guidelines of their own and their advisors when it comes to handling soil compaction, while there are essentially no monitoring data concerning farmers' fields.

There is less risk of soil compaction by machines in small-holder farming in China, for example, than in the mechanized agriculture of Europe, North America, and Oceania. There is also no governmental policy aimed at preventing soil compaction in China. However, the intensive cultivation practices and irrigation, and the silty texture of the dominant loss soils in north China are conducive to soil compaction, and there is therefore a continuous search for soil conservation practices that decrease the risk of soil compaction and improve soil structure [60,61]. A combination of tillage practices in sequence appears to be the best strategy [62–64]. This holds for no-till as well. However, it has to be combined with subsoiling once in a few years, as also discussed for the no-till agriculture in Argentina by Peralta et al. [44]. The need for combining tillage practices in China also follows indirectly from the increasing interest in subsoiling during the last two decades (e.g., Figure 1 [24]).

The FAO voluntary guidelines for sustainable soil management do provide technical and policy recommendations to prevent and mitigate soil compaction [65]. Though qualitative and without threshold values, these guidelines are interesting because they address not only the machines and vehicles in the field, but also the importance of crop type and crop rotation, soil organic matter content, soil macrofauna, and microbial and fungal activities. Amelioration measures are not explicitly mentioned, apart from the recommendation to also grow crops with strong tap roots able to penetrate and break up compacted soils. Next to soil compaction, the FAO guidelines also present recommendations to prevent and mitigate nine other soil threats [65]. The need for a more coherent and integrated soil management concept was also recently emphasized by Rietra et al. [47]. They presented a roadmap for developing high-yielding, soil-improving, and environmentally sound cropping systems. This roadmap involves an iterative selection and optimization of site and farm specific crop husbandry and soil management practices, including the selection of machines that minimize soil compaction.

Evidently, preventing soil compaction from happening is too simple a strategy to address soil compaction. Rather, a toolbox of strategies and management practices is needed, which can be used to develop and implement site-specific management measures. Our study provides evidence that both prevention, amelioration, and alleviation measures have value, depending on the site-specific conditions. These measures provide net economic benefits for farms in most cases, through increases in crop yields and resource use efficiency [22,66]. The selection of the most appropriate measures will likely improve, and the effectiveness of these measures will likely increase, when more data become available at the farm level, related to the state and impact of soil compaction, through routine monitoring.

4.4. Limitations of Our Study

We focused on the recent literature (2000–2019/2020), because there are some excellent papers that reviewed and analyzed the older literature, e.g., [23,67], and not many studies have been conducted in small-holder agriculture before 2000. We examined literature from both mechanized agriculture and small-holder farming to make comparisons between these two types of agricultural systems, based on the literature from 2000–2019/20. We note that the literature from S-farming countries from before 2000 has not been analyzed in a systematic manner yet, apart from the studies by Hoogmoed et al. [68], and the reviews by Laker and Nortjé [8], and Peralta et al. [52].

Further, we note that the machine weight is rapidly increasing over time [69], not only in M-agriculture countries, but also in some S-farming countries. Hence, the rough categorization in S-farming and M-agriculture countries may not be the best way to examine differences between mechanized and smallholder agriculture, although this comparison provided new insights, e.g., related to the type of measures applied in the two types of agriculture.

Crop types may respond differently to compacted soils and thereby also to prevention, amelioration, and alleviation measures, because of differences in root morphology and physiology [54,70]. We selected cereals as test crops because these were mostly used and have a more or less uniform response. Thereby, we excluded 183 studies with non-cereal test crops out of the 719 available studies (25%).

Further, we excluded studies that combined various measures, e.g., controlled traffic combined with no tillage, controlled traffic combined with deep tillage, tillage combined with residue management levels, and irrigation combined with subsoiling. The exclusion of these studies does not mean that these studies are less relevant. Instead, it requires another study to infer useful conclusions from these combined-measures studies.

5. Conclusions

Our meta-analysis included 77 studies from 28 countries (32 studies from 16 countries for mechanized agriculture (M-agriculture), and 45 studies from 12 countries for smallholder farming (S-farming)) all related to the effectiveness of soil compaction prevention, amelioration, and alleviation measures. These studies were published between 2000 and 2019/2020 and thus are relatively recent. Prevention measures were mostly studied in M-agriculture, while remediation and alleviation measures were mostly studied in S-farming.

Soil compaction prevention, through controlled traffic, had a positive effect on crop yield in both M-agriculture (+38%) and S-farming (+16%) countries, and led to a lower soil bulk density in topsoil and subsoil (−4% to −6%), and to a lower soil penetration resistance (−26% to −33%). These results confirm earlier estimates for M-agriculture countries but now show that controlled traffic also holds promise for S-farming. However, it is not clear whether controlled traffic is economically profitable in S-farming. Soil compaction prevention through no-till had negative effect on crop yield, while bulk density was increased, in both M-agriculture and S-farming.

Soil compaction amelioration through deep tillage (including subsoiling) had positive effects on crop yields (+9% to +10%), while soil bulk density was decreased by about 3%. These results confirm earlier observations for M-agriculture, but we show that these observations are also valid for S-farming. The relatively large number of studies related to deep tillage in S-farming suggest that subsoil compaction is increasingly seen as a constraint to crop production in the countries with S-farming.

Irrigation was an effective alleviation measure for subsoil compaction, though only reported for S-farming. The large mean effect size for crop yield (+51%) reflects that compacted soils impede root elongation and thereby enhance the impacts of drought, though the effect of irrigation likely relates not only to alleviation of drought related to compacted subsoils. Crop residue mulching and manure application had a small effect on alleviating compacted subsoils.

Soil penetration resistance and bulk density were mostly used as state indicators. Effect sizes of measures on soil bulk density were small (<10%), indicating that bulk density is not a sensitive indicator for assessing the effects of measures. Effect sizes of crop yield as an impact indicator were relatively large, but variable because of interfering factors (climate, soil texture).

A toolbox of soil compaction prevention, amelioration, and alleviation measures is also needed because the cause of soil compaction and the responses of measures are site-specific. Our meta-analysis indicates that such a toolbox is needed for M-agriculture and S-farming.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11050645/s1, Figure S1: Changes in the number of papers published per year, studying the relationships between soil compaction and crop yield.; Table S1: Data and information used for this meta-analysis; Table S2: Summary overview of effects sizes of soil compaction prevention, remediation and alleviation measures on crop yields, soil bulk density (BD), and soil penetration resistance (PR), shown for three categories of studies.

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Notes

[1] The DPSIR framework stands for Driving forces, Pressure, State, Impact and Responses. It allows for analyzing and understanding the cause-effect chain of soil comapction in a systematic manner, as further discussed in the Discussion section.

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