**Evaluating effect size distribution of different regenerative agriculture practices across soil, climatic and topographical factors**

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**Abstract**

Soil conservation practices (SCPs) related to regenerative agriculture are increasingly promoted for enhancing ecosystem services while supporting sustainable crop production. However, their effects on yield remain context-dependent and inconsistently reported. Here, we conduct a global meta-analysis of 10,002 paired observations from 732 studies, evaluating yield changes across four RAPs—agroforestry (AF), cover cropping (CC), no-tillage (NT), and organic farming (OF)—relative to conventional tillage. Integrating environmental moderators, including climate, topography, and detailed soil properties, we assess effect size distributions across spatial and agronomic gradients. Results indicate that, overall, RAPs increased crop yields by a modest 0.7%, with AF and CC showing the highest gains (12% and 7.5%, respectively), while NT and OF showed slight yield declines (−0.7% and −2%). Yield benefits were more pronounced in arid and temperate climates, low fertility soils, and elevated terrains. Crop-specific responses varied, with maize and cash crops benefiting most. Management combinations under NT influenced outcomes significantly, with nutrient input and soil cover proving essential in arid environments. These findings underscore the need for site-specific, integrated implementation of (SCPs) and highlight their potential to enhance productivity in degraded or climatically constrained regions.

1. **Introduction**

More than 70% of the Earth’s land area which was initially covered by forests and wildlands have been transformed to various use by human being1. A large fraction of such use is devoted to agriculture occupying about 40% of the world land area. However, food production results in a huge environmental footprint with one-third of soils in the world being degraded and fertile soil being lost at the rate of 24 billion tons of topsoil every year2 along with about 34% of global greenhouse gas emissions3. Meanwhile, it is projected that food production would have to increase in the future to satisfy both the need of the global growing population and the increase in per capita demand4. In this context, sustainable pathways that would contribute to land restoration, biodiversity protection and GHG mitigation are more and more emphasized.

Regenerative agriculture has emerged as an alternative farming strategy seeking to achieve global food security by reducing the use of external inputs, improving soil health and minimize environmental damage5-7. The RA involves different soil conservation practices (SCP) such as reduced or not tillage (NT), cover crop (CC), perennials and agroforestry (AF), organic farming (OF), intercropping (IN) as well as crop-livestock integration6,8. Previous studies reported potential beneﬁts of different RAP for increasing soil organic carbon (SOC) and soil water uptake as well as GHG mitigation climate mitigation 6,8,9. Thus, although environmental benefits seem to be considerable, yield outcomes through the implementation of different SCP are subject to many controverses.

Some existing studies have shown that SCP could potentially result in increasing yields10,11 while others reported a neutral or declining trends12,13 after implementation. While evaluating the outcome of different crops and environmental variables on NT as compared to conventional tillage (CT) yields, Pittelkow, et al. 14 show that NT impact on yield is dependent upon the region with increasing trend in moisture-limited arid regions while declining patterns are observed in tropical regions with maize-based systems. A global meta-analysis based on740 paired measurements from 90 peer-reviewed articles show that NT increased barley yield by 49% especially in dry climate15. In a drought period, about 60% higher maize yields were observed under NT management compared to CT16. However, contrary trends are also reported with the application of crop rotation, residue management, and no-tillage having no effect on yield stability relative to CT17. The same study showed that OF had 15% lower yield compared to CT.

Under AF management, findings show that yield either increased by 7 – 16 % in crop yield especially in subtropical and tropical zones18, or reduced by 2.6 % in European areas depending on the density and age of the trees19. While about 14% yield increase is reported under CC especially in coarse soil texture and dryland areas along with the use of leguminous cover crops20, about 3% yield reductions were observed especially for cash crops in temperate soils21,22. About 10% decrease in wheat yields were observed following cover cropping23. Findings related to the analysis of the benefits and management of IN practices revealed that average grain yields were 22.3% higher in intercropped systems compared to monocultures of the same crops24 while other reported 39% reduction in primary maize yield compared to pure maize yield25. In context whereby there is no significant increase or decrease, some studies reported that yields could be sustained for longtime under RAP especially for degraded soils26.

The discrepancy of yield outcomes under different RAP have thus shown that various factors interplay to determine the magnitude and direction of crop yields for farmers. However, there is a need of having a better understanding on how environmental factors affect crop yield changes under different RAPs. Though previous meta-analysis studies have analyzed the variation in productivity between regenerative and CT managements, they mostly focus on a single type of RAP 11,27-29 without investigating their comparative potential across various factors and crop types at a global scale. To our knowledge, these studies do not include or have incomplete records of key soil variables such as bulk density, soil organic carbon, phosphorus, pH, texture, cation exchange capacity, or topographic variables such as elevation and slope or climate variable such as temperature, precipitation, crop growing degree days etc.

Consequently, these studies do not involve a large range of environmental factors except for some NT studies which considered alongside management variables such as soil texture 11,30 or aridity27 as well as climate zones or climatic variables such as temperature and precipitation. However, advances in remote sensing technology in recent decades have resulted in the existence of global earth data with the affordability and accessibility of satellite imagery which provide valuable information on environmental conditions and variables related to soil properties (e.g. soilGrids), climate, topography etc. which in turn are potential factors affecting crop yields31-33. Our current study is unique in that it focuses on different RAPs and their influence on relative crop yields across climatic, topographic variables and additional soil properties beyond texture. Therefore, the objective of this paper is to take an advantage of global earth data and field experiment data to assess the distribution of RAPs related relative yields among different conditions defined by environmental factors at a global scale. A profound understanding of the

variability of RAP related yields across different influential factors should facilitate deeper insight into selecting appropriate CA practices in different regions and thereby support targeted planning for sustainable development.

1. **Materials and methods**
   1. **Data collection**

Different global meta-analysis data from Xu et al.11, Jian et al.34, Pittelkow et al.27, Xia et al.35, Verret et al.36, Ding et al.37 and Felix et al.28 were combined in the present study. This resulted in a total of 10 232 comparisons between RAP (i.e. regenerative agricultural practices) and CT (i.e. conventional tillage), from 758 publications covering 773 sites worldwide (Figure 1). After compiling the data, the crop types were classified into seven groups with the most cultivated crops in the world such as maize, wheat, soybean and rice considered separately. The remaining crops were categorized cereal, cash-crop and vegetable & fruits and others (see Table 1 in supplementary material). The compiled data cover the following RAP practices: Agroforestry, Cover Crop, No-tillage, organic farming.

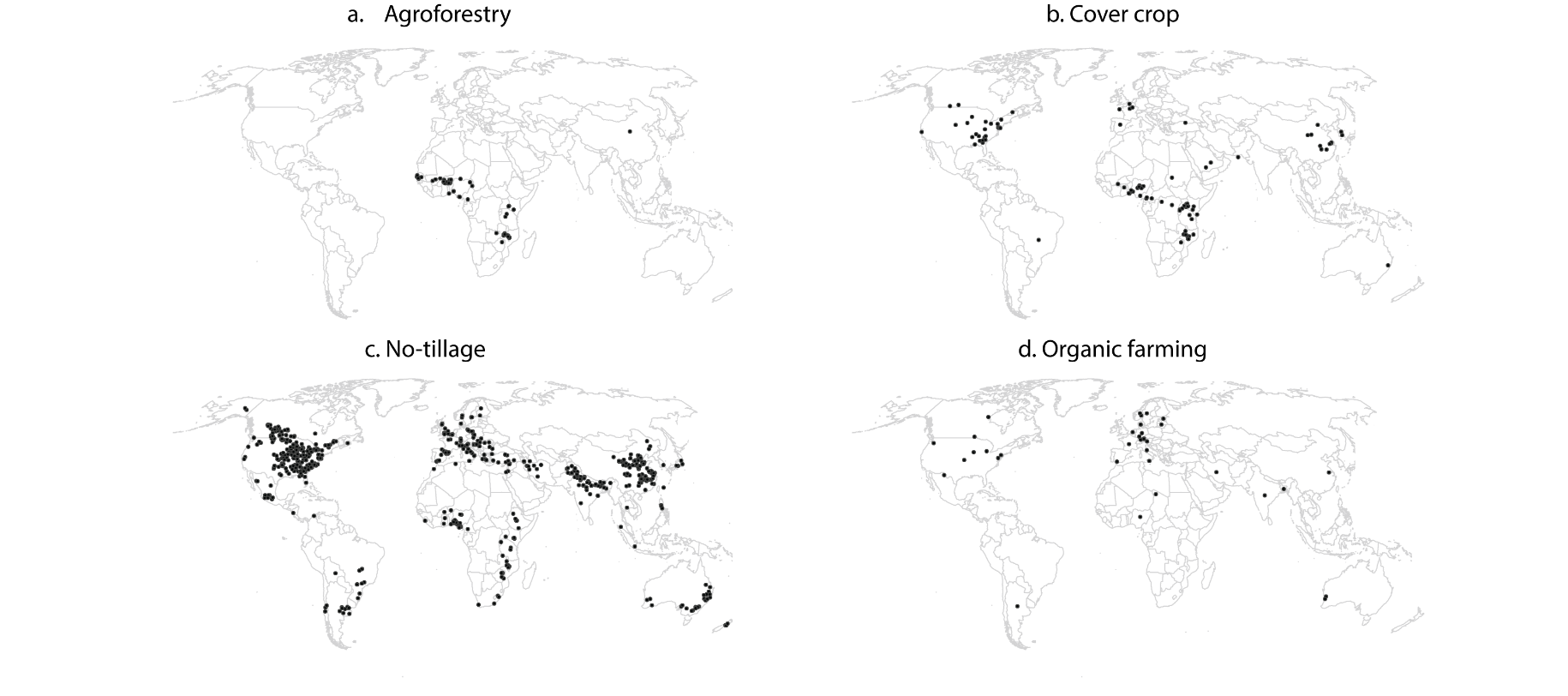


Figure 1: Global distribution of the study sites

* 1. **Environmental and management effect size moderators**

The impact of the RAP on effect size (ES)was assessed based on 3 environmental components: climate, soil properties and terrain. For each of the three components, several indicators were identiﬁed (Table 1).

Climate, soil properties and terrain variables have been documented to have a major impact on crop growth and food production38-41. As climate variables, precipitation and temperature are closely associated with crop growth and crop yield and affect soil moisture status which in turn determines whether water might be a limiting factor the crop phenological development. The aridity considered in this study as climate indicator is defined as the ratio of precipitation to potential evapotranspiration and

is a measure of moisture availability for crop growth. The global aridity index for the 1970–2000 period was obtained from the Consortium for Spatial Information (1 km)42. The Growing Degree (GDD) measures the heat accumulation over the growing season and is a measure of the relationship between temperature and plant development. The Growing degree days (GDD) used in this based was sourced from Ahvo, et al. 43.

Terrain attributes interact with weather to affect soil temperature and moisture44,45. Water stress occurs most likely in upslope positions with lower and higher variability in yields compared to lower slope positions46-48. Terrain indicators such as terrain and slope (1 km) were obtained via the platform provided by the global study of Amatulli, et al. 49.

Soil properties determine the local environment for crop growth by affecting soil aeration, nutrient cycling and root growth50,51. For instance, soil texture affects the available water capacity in the root space while soil pH influences the availability of nutrients to plants and microbial activity52,53. Global soil properties such as soil texture (sand, silt, clay), bulk density (BD), soil organic carbon (SOC), pH were downloaded from the SoilGrids (250 m) platform 54. The global stock of soil Olsen phosphorus came from the global study carried out by McDowell et al.55

In addition, additional management variables such as cover crop (yes/no), N fertilizer (yes/no), weeding (yes/no) and rotation (yes/no) were considered for NT. Consequently, under each component, the distribution of the ES under NT was further analyzed for each of these management variables.

* 1. **Data analysis**

The data analysis focused on the effect size (ES), i.e. the response ratios (RR) of crop yield to these management systems and was assessed by taking the natural logarithm calculated of RR following Luo, et al. 56 : RR = ln(XT/XC) where XT and XC are the yield value under treatment (NT, AG, CC, or OF) and control, respectively. Moderator analysis was conducted to determine the RAP effects ES. This analysis was carried out by grouping the metadata into the following categories:

* Crop groups. The previously defined crop groups were considered: maize, wheat, soybean and rice, cereal, cash-crop and vegetable & fruits and others.
* Bulk densities. Low values of BD describe permeable soils allowing plant to reach the nutrient and water easily while high values denote a compacted soil with high mechanical impedance resulting in limited roots growth. It was categorized into three different categories: low (< 1.2 kg/dm3) , moderate (1.2 kg/dm3 < BD < 1.47 kg/dm3), high (BD > 1.47 kg/dm3)57. cite
* pH. Three categories were considered: acidic soils (pH < 6.3,) neutral soils (6.3 < pH < 7.4) and alkaline soils (pH > 7.4). cite
* Phosphorus. The P distribution classes were low: P < 10.9 mg/kg, moderate: 10.9 mg/kg < P < 21.4 mg/kg and High : P > 21.4 mg/kg. cite
* Soil organic carbon. Three categories were considered: SOC < 5 g/kg, 5 g/kg < SOC < 10 g/kg and SOC > 10 g/kg. cite
* Soil texture: These textures were grouped into fine (clay, silty clay loam, clay loam, and sandy clay), medium (silt loam and loam), and coarse (sandy loam and sandy). Cite
* # 1: fine (clay, silty clay loam, clay loam, and sandy clay) : cl SiClLo ClLo SiCl SaCl SaClLo
* # 2: medium (silt loam and loam) Si SiLo Lo
* # 3: coarse (sandy loam and sandy) SaLo Sa LoSa
* Aridity. It was divided into five categories: Hyper-Arid (AI < 0.05), arid (0.05 < AI < 0.2), semi-arid (0.2 < AI < 0.5), sub-humid (0.5 < AI < 0.65) and humid (AI > 0.65). cite
* Growing degree days. Four classes were considered: unsuitable (GDD < 800°C/y), suitable (800°C/y < GDD < 2700°C/y), heat Stress (2700°C/y < GDD < 6000°C/y), high heat Stress (4000°C/y < GDD < 6000°C/y). cite

Using bootstrapping, which involves resampling the response ratio mean 1000 times, 95% confidence intervals were determined for each category. The effect size was deemed non-significant if the confidence interval include zero.

Table 1: Environmental variables (in bracket are abbreviations)

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Indicators | Unit | Resolution |
| Soil properties | Soil texture | % | 250 m |
| pH |  | 250 m |
| soil organic carbon (SOC) | g/kg | 250 m |
| Soil Olsen phosphorus concentrations (phosphorus) | mg/kg | 1000 m |
| Bulk density (bd) | kg/dm³ | 250 m |
| Terrain | Slope | % | 0.0083° |
| Digital elevation model (dem) | m | 0.0083° |
| Climate | Growing degree days for maize (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for wheat (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for rice (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for soybean (GDD\_maize) | ° C | 0.0083° |
| Aridity index (aridity) | °C/y | 0.0083° |

# Statistics ???

# May be multivariate statistics with Principal Component Analysis: conduct multiple linear regressions with a stepwise method using the derived Principal Component factors with eigenvalues greater than 1 for (1) all data and (2) for each climatic regions.???

* 1. **Publication bias and sensitivity analysis**

# The consideration of the variance for each study is usually required in meta-analysis for conducting using a funnel plot analysis. However, the majority of the studies did not provide the variance for such purpose. Therefore, the density plots of the different RAP were created to check the distribution of all individual effect sizes in the dataset to check potential publication bias 58,59. Moreover, a sensitivity analysis was carried out using the Jacknife approach to determine the robustness of the analysis60. Every study was given a distinct study ID during the Jacknife analysis process, and data from one study was removed from the database for every computation.

1. **Results**
   1. **Analysis of the entire data set across regenerative agriculture practices, crops and environmental variables**

# Considering the entire dataset, the soil conservation practices increased crop yield by 0.7% (Fig. 2). However, the yield changes varied across practices and crops. Specifically, significant yield increases were observed with AF and CC with mean increases of 12% and 7.5% respectively. By contrast, the implementation of NT and OF tend to result in decrease in yield by 0.7% and 2% respectively. For the crops, significant yield increases were recorded only with maize and cash crops with mean increases of 1.7% and 0.7% respectively.

# The outcome of the analysis also showed that the impact of the practices on crop yield varied depending on climate, soil properties and topography. Considering the different climate types, arid regions displayed the greatest increase in yield, with a mean increase of 3.8% followed by a 1.8% mean increase in temperate regions (Fig.2). The trend for the arid regions was further confirmed with the aridity index with 2.7% and 9% mean increase in yield respectively for the semi-arid (0.20 -0.50) and the arid (0.05 - 0.20) areas. Meanwhile, there appeared to be decrease in yield in continental regions while no significant effect occurred in tropical areas.

# Ranges of growing degree days (GDD) for which significant changes in yield occurred varied with crops. Maize recorded a large yield increase with GDD between 2700 – 4000 (1.9%) and 4000 – 6000 (5.7%). Rice recorded high yield increase within the following range of GDD: < 800 (11.6%), 4000 – 6000 (2.8%) and 6000 – 10000 (2.7%). The highest yield increase for soybeans was in the ranges: 2700 – 4000 (1.9%) and 4000 – 6000 (5.7%). The most significant increase occurred for wheat within 800 – 2700 (1.8%) and 6000 – 1000 (3.8%).

# When considering soil properties, the highest yield increase was recorded for crops planted in low SOC soils (10%), coarse texture (1.76 %), in alkaline (1.38 %) and acid soils (1.24%), in soils with less than 10.9 mg/kg phosphorus content (1.3%) and soil with 10.9-21.4 mg/kg phosphorus content (0.5%) as well as in soils with small (< 1.20 kg/dm, 1.05 %) or medium level bulk density (1.20-1.47 kg/dm3, 1.3%). By contrast, significant yield decrease was recorded for crops grown on neutral soils. Most substantial yield increase was recorded for crops grown in Lixisols (18.3%), Aeronosols (14.6%), Calcisols (12.7%), and Regosols (4.6%), Acrisols (3.7%), Luvisols (2.3%) and kastanozems (2.9%). On the other hand, significant yield decrease was recorded for Alisols (17.5%), Gleysols (11.3%) and Phaeozems (4.3%).

# The distribution of ES across slope gradient varied, with positive yield gain in gently sloping (0.53 %) areas (5-15 %) with the most significant observed for gentle (3.4 %) slopes (1–5%) and strong (11 %) slopes (15–30%).The trend for the landform showed generally positive yield increase except for high plain areas (Hi\_plain), valley slope (Val\_sl), moderate hills (Mod\_hills) which are mostly located in lower elevation areas. On the other hand most significant yield increase occurred on landform characteristic of high elevation areas between the Mountain valley slope (Mtn\_vs) to the mountain summit (Mtn\_sumt).

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Figure 2: Distribution of the percentage change of the effect size between regenerative agriculture practices, crop groups, soil properties, terrain, and climatic variables (RAP: Regenerative agriculture practices, V\_F\_others: Vegetable, fruits and others, P: Phosphorus, BD: bulk density, GDD: growing degree days, Mtn\_sumt: Mountain summit, Cliff\_sl: Cliff slope, Lwhi\_mtn: Lower/hilly mountain, Shills\_dcsl: Steep hills / dissected cliff slope, Lhgsl\_steep: Large highland slope steep, Lhgsl\_mod: Large highland slope moderate, Mtn\_vs: Mountain valley slope, Mod\_hills: Moderate hills, Tfphi\_dis:Terrace/fan/plateau (high, dissected), Tfphi\_surf: Terrace/fan/plateau (high, surface), Val\_sl: Valley slope, Tfplw\_dis: Terrace/fan/plateau (low, dissected), Tfplw\_surf: Terrace/fan/plateau (low, surface), Hi\_plain: High plain (Sinks < 50%), Lw\_plain: Low plain (Sinks < 50%)). Effect size (ES) represents the yield change in relation to control in experiment; positive effect size means treatment in experiment resulted in higher yield compared to control, negative effect size means treatment in experiment resulted in lower yield compared to control. The symbols used in the figure include dots with error bars, representing the overall mean effect size values ±95% confidence intervals. Categories whose 95% confidence intervals do not include 0 (represented by the vertical red lines) have significant differences between regenerative agriculture practices and controls

* 1. **Effect size distribution across climate variables for different soil conservation practices**

The trend across specific soil conservation practices showed that AF recorded a higher yield increase (12 %) than CC (7 %), NT (-0.7 %) and AF (-2 %). Cropwise, yield increase occurred mainly with maize under AF, other cereal with CC and wheat with NT. For the climate regions, the record for arid regions were actually related to AF and NT with a higher increase for AF. While for more humid areas, a higher yield increase trend is observed for AF and CC especially with aridity index above 0.50.

Generally, high GDD (> 4000 oc) resulted in higher yield increase with maize under AF and CC. Meanwhile, significant increase at lower GDD (< 800) was only recorded for maize under OF and for rice under NT and OF. For both rice and soybean, there appeared to be higher yield increase above 4000 oc under CC. For GDD between 800 and 2700 oC, wheat recorded a significant yield increase under CC and OF while above 6000 oC GDD, similar tend only occurred with CC.

Considering the soil properties for each management, yield increase generally occurred with decreasing bulk density especially under AF, CC and OF. Increasing P resulted also generally in increasing yield except for larger P (> 21.4 kg/mg) content which translated into negative impact under CC, NT and OF. On the other hand, higher P (> 21.4 kg/mg) significantly increased yield in AF (38 %) systems. All SCP present high yield increase in soils with low SOC (< 5 g/kg) with most SCPs while for soils with higher SOC (> 5 g/kg), AF and CC still recorded high yield increase but in lower magnitude. Coarse texture soil recorded positive increase across all SCP except OF but the significant yield records were only found with CC (9%) and NT (3%).

Considering elevation, significant yield increase was observed for high plain areas above 250 m for both AF and CC. This is further confirmed for these two SCP by the distribution of the effect size across the different landform with generally positive yield increase from the mountain summit to the moderate hill. OF also recorded similar trend in areas characterized by large highland slope moderate (Lhgsl\_mod). In addition, CC and NT recorded a significant yield increase for landforms occurring mostly at lower elevations especially for for areas dissected terrace/fan/plateau (Tfphi\_dis) and valley slope (Val\_sl) for NT on the one hand and for dissected terrace/fan/plateau (Tfphi\_dis), low surface Terrace/fan/plateau (Tfplw\_surf) and high plain (Hi\_plain) areas for CC. For slope, it appeared that most significant yield increase are recorded for AF on level to gently sloping areas (slope: < 15%) while on gentle (1-5 %) or strong slopes for CC (< 15%).

The performance of the SCP varies across different soil types. For AF, significant yield increase and decrease occurred with Acrisols and kastanozems respectively. The most significant yield increase records were with Cambisols, Luvisols and Vertisols under CC and with Alisols, Fluvisols, Phaeozems under NT. With Calcisols, Gypsisols, Histosols, Luvisols NT recorded a significant yield decrease. OF recorded a high yield increase with Ferranosols and Phaeozems, although not significant with the latter.

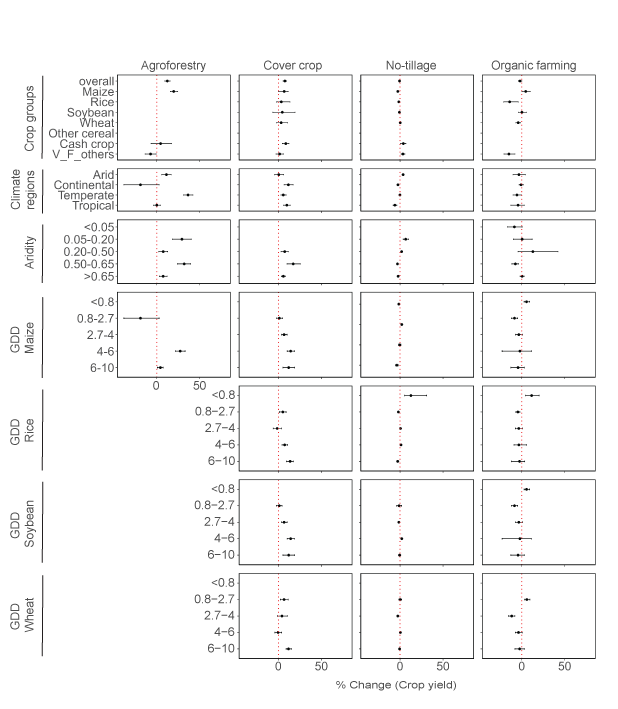


Figure 3: Distribution of effect size across crop groups and climatic variables for different regenerative agriculture practices. The symbols used in the figure include dots with error bars, representing the overall mean effect size values ±95% confidence intervals. Categories whose 95% confidence intervals do not include 0 (represented by the vertical red lines) have significant differences between regenerative agriculture practices and controls. V\_F\_others: Vegetable, fruits and others, GDD: growing degree days.

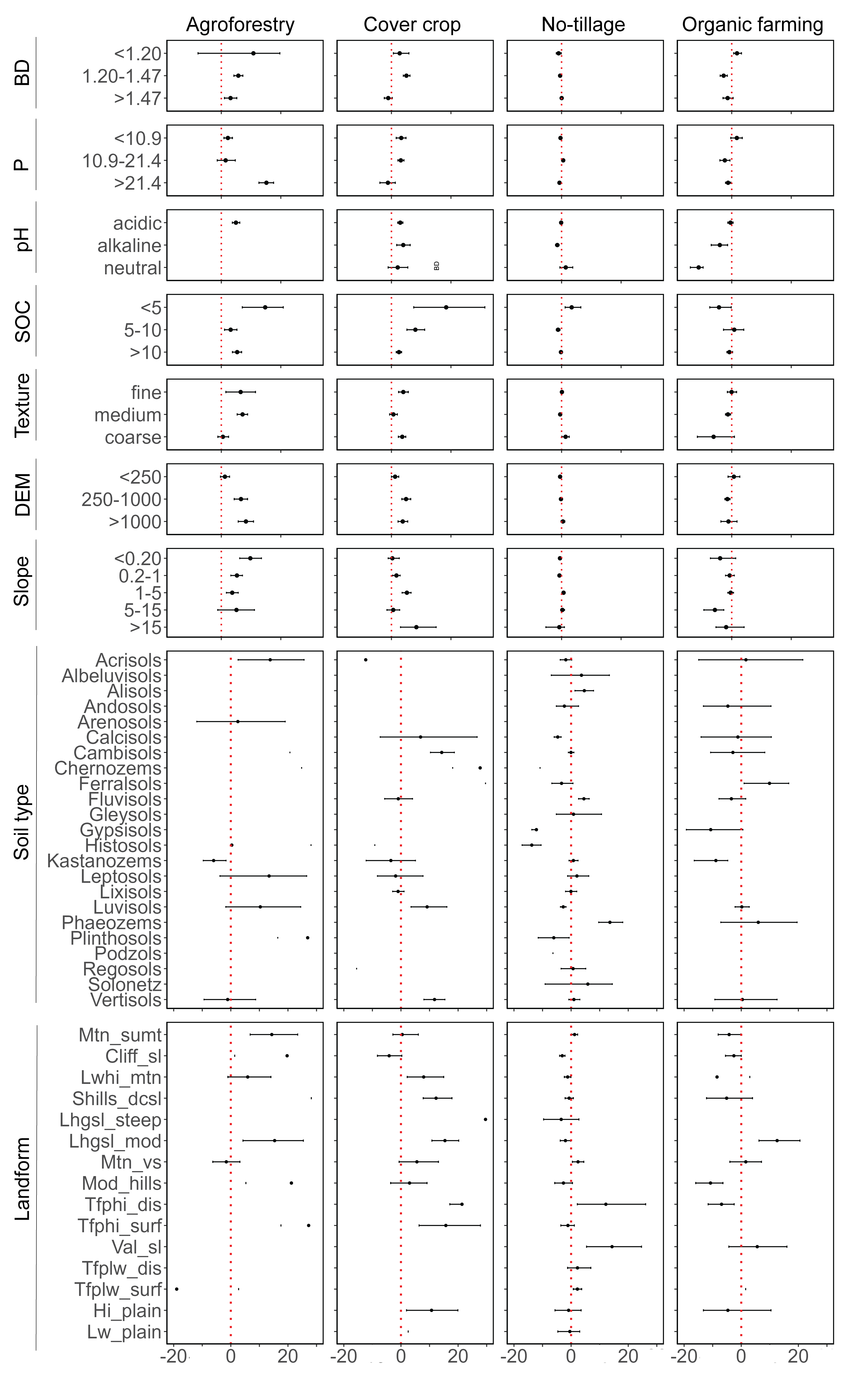
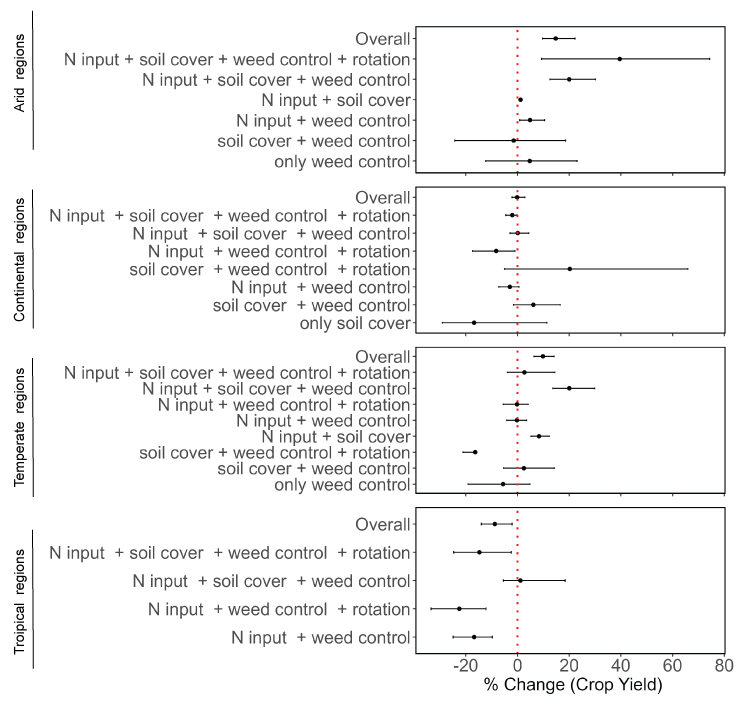


Figure 4: Distribution of effect size across soil properties and terrain for different between regenerative agriculture practices. P: Phosphorus, BD: bulk density, DEM: digital elevation model**.** The symbols used in the figure include dots with error bars, representing the overall mean effect size values ±95% confidence intervals. Categories whose 95% confidence intervals do not include 0 (represented by the vertical red lines) have significant differences between regenerative agriculture practices and controls.

* 1. **Effect size distribution across different no-tillage management practices**

Yield responses to no-tillage (NT) practices varied substantially across climatic regions and management configurations (Fig. 5). NT implementation led to significant average yield increases in arid (14.7%) and temperate (9.8%) regions, while yield declines were observed in continental (−0.1%) and tropical (−8.7%) zones. The most substantial benefits were recorded in arid areas, particularly under integrated management practices combining nitrogen input, soil cover, weed control, and crop rotation (up to 39%), followed by combinations without rotation (e.g., 20% with N input + soil cover + weed control). In temperate climates, similar management strategies also improved yields, with notable increases under N input + soil cover + weed control (20%) and N input + soil cover (8.3%). Although NT showed overall limited benefit in continental regions, specific managements such as soil cover + weed control + rotation yielded a 20% increase. In contrast, tropical regions experienced general yield declines under NT, with only minimal gains (1.1%) observed when N input, soil cover, and weed control were jointly applied.

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# Figure 5: Distribution of effect size across different no-tillage management practices. N: nitrogen. In bracket are the number of observations per management.

* 1. **Publication bias and sensitivity analysis**

The density distribution plot and the histogram showed that the observations related to the different SCPS were close to the normal distribution (Fig. 6a,b), suggesting that the meta-analysis was not subject to publication bias. Although a small number of studies produced estimates that fell outside the 95% confidence interval when removed, the results of the Jackknife sensitivity indicated that the exclusion of individual studies did not substantially alter the pooled effect, as most of the resulting estimates still remained within the original 95% confidence interval (Fig. 6c).

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# **Figure 6:** The (a) density plot (b) the sensitivity analysis for each regenerative agriculture practice. The lower and higher 95% confidence intervals are provided as dashed red lines. AF: Agroforestry, CC: cover crop, NT: no-tillage, OF: organic farming.

1. **Discussion**

The implementation of CSP at a larger scale requires a thorough understanding of processes and mechanisms that affect crop yield across different environmental contexts. Although previous findings have reported the contrasting results of such practices with cases of yield increase, decrease or maintenance, most do not provide deeper insight into the inherent factors affecting such yield dynamics 10,12,13. However, such knowledge is crucial for context-specific implementation of such practices. This study provides a comprehensive assessment of the effects of different soil conservation practices on crop yield, considering a broad range of crop groups, climate regimes, soil properties, and terrain characteristics. The overall finding that SCPs associated with regenerative agriculture can lead to modest but significant increases in crop yield, with a pooled average increase of 0.7%, supports growing evidence that sustainable intensification is achievable through nature-based solutions. However, the magnitude and direction of yield responses varied considerably depending on the specific practice, crop type, and environmental context created by the interplay of climate regimes, soil properties, and terrain characteristics.

* 1. **Crop yield change across practices**

Among the practices evaluated, agroforestry (AF) and cover cropping (CC) demonstrated the most consistent positive impacts on yield, with mean increases of 12% and 7.5%, respectively. These findings align with previous research highlighting the beneficial effects of diversified cropping systems and improved ground cover on soil moisture retention, nutrient cycling, and microclimate moderation (Jose, 2009; Poffenbarger et al., 2015; Basche et al., 2016). In contrast, no-tillage (NT) and organic farming (OF) were associated with modest yield declines (−0.7% and −2%, respectively), which may reflect challenges related to nutrient availability, weed pressure, or delayed adaptation of these systems in certain contexts (Pittelkow et al., 2015; Seufert et al., 2012).

* 1. **Crop yield change across specific crops and growing degree days**

Crop-specific responses also varied. Maize and cash crops showed significant yield gains, while other crop types exhibited mixed responses. These findings suggest that certain crops may benefit more from SCP, potentially due to their physiological traits, input requirements, or interactions with improved soil and microclimatic conditions. Maize, being a high-input crop with rapid biomass accumulation, may respond more favorably to soil fertility improvements and enhanced water retention often associated with SCP (Thierfelder et al., 2015; Tittonell et al., 2012). Its favorable performance of maize under AF may be attributed to the multifunctional benefits of trees—such as nitrogen fixation, enhanced nutrient cycling, and shade-induced water conservation—which can support maize growth, especially in rainfed or degraded systems (Jose, 2009; Cardinael et al., 2018). On the other hand, higher GDD (>4000°C) tended to correlate with greater yield responses for maize, soybean and wheat, particularly when combined with adaptive management practices such as AF and CC compared to NT and OF. This trend under AF and CC might further indicate that better enhance the crop’s ability to utilize accumulated heat effectively through improved microclimate and soil health (Mbow et al., 2014; Tully & Ryals, 2017) than NT and OF.

Furthermore, most cases of higher yield increase at very low GDD (<800°C) for maize, rice, and soybean occurred under OF. These might reflect short-season varieties or early maturing systems (van Oort & Zwart, 2018). Such pattern suggests that OF practices may confer particular advantages in cooler or short-season environments, where thermal accumulation limits crop development. In such conditions, the gradual nutrient release from organic amendments aligns more closely with slower crop growth, enhancing nutrient use efficiency (Berry et al., 2002; Reganold & Wachter, 2016). Improved soil structure and moisture retention under organic management can further buffer crops against thermal limitations (Lotter, 2003), while reduced pest and disease pressure in cooler climates minimizes reliance on synthetic pesticides (Altieri et al., 2015). Moreover, conventional systems often perform suboptimally in low-GDD regions, which may amplify the relative gains from organic practices. For legumes like soybean, biological nitrogen fixation reduces dependence on external N inputs, favoring organic systems where synthetic fertilizers are excluded (Drinkwater et al., 1998). These findings underscore the importance of agroecological context in assessing the performance of farming systems (Seufert et al., 2012).

* 1. **Crop yield change across climate types**

There were variations in yield increases based on climate types and management practices. CC exhibited most yield increase for the continental, temperate and tropical zones while significant yield gains were also observed for AF and NT in arid regions. This might be due to the fact that cover crops struggle to establish themselves without sufficient precipitation with the possibility of competition for moisture reducing the yield of primary crops. In such instances, strategies such as NT or AF may be more beneficial in arid environments as suggested by the gain increase observed in 0.05–0.20 aridity range. Such pronounced benefits for the implementation of such SCPs in arid regions, suggest that these practices may be particularly advantageous in water-limited environments where conventional methods often lead to soil degradation and reduced productivity. This further highlight the potential of these practices to enhance resilience and productivity under increasingly dry conditions (Thorpe et al., 2022), a finding that is especially relevant given the projected expansion of arid zones due to climate change (IPCC, 2021). In more humid regions (aridity index >0.50), AF showed highest yield gain especially in temperate regions compared to CC. These practices likely enhance nutrient cycling, prevent erosion, and improve soil structure—benefits that are especially valuable in wetter environments where nutrient loss and leaching are common (Kaye & Quemada, 2017; Poeplau & Don, 2015).

* 1. **Crop yield change across soil properties**

Analysis showed that most of SCPs significantly increased crop yields in soils with low organic carbon (<10 g/kg), coarse texture, and either acidic or alkaline pH, particularly in nutrient-poor conditions such as low to moderate phosphorus levels and low to medium bulk density. These findings suggest that SCPs are particularly effective **in nutrient-poor or structurally degraded soils**, likely due to their role in enhancing nutrient cycling, improving soil structure, and increasing biological activity (Lal, 2004; Six et al., 2002). This is further corroborated in the ES distribution in the different soil types, with the greatest yield improvements seen in marginal soil types like Lixisols, Arenosols, and Calcisols, while yield declines occurred in more chemically or physically constrained soils such as Alisols and Gleysols.

However, AF and CC only sustained moderate gains in higher SOC conditions, reflecting diminishing returns in already fertile environments. Coarse-textured soils recorded positive yield effects across all SCPs except OF, with statistically significant results under CC (9%) and NT (3%), consistent with evidence that conservation practices improve water retention and soil structure in sandy soils (Blanco-Canqui & Lal, 2009). Specificities such as yield reductions in **neutral pH soils** and **high phosphorus soils (>21.4 mg/kg)** under certain SCPs – CC, NT, OF - may reflect nutrient imbalances or diminished relative benefits in already fertile systems.

The significant yield increase observed in agroforestry (AF) systems under high phosphorus levels (>21.4 mg/kg) aligns with research showing that while AF systems enhance nutrient cycling, they still benefit from phosphorus supplementation, especially in P-deficient soils. Phosphorus is often a limiting nutrient in weathered tropical soils due to fixation, and its availability is essential for both plant growth and biological nitrogen fixation - especially in leguminous tree species common in AF (Sanginga et al., 1995; Richardson et al., 2009). Studies have shown that P inputs can stimulate microbial activity, mycorrhizal associations, and root development, resulting in greater nutrient uptake and biomass production (Cardoso et al., 2003; Isaac & Borden, 2019). Thus, the 38% yield increase under high P in AF systems likely reflects the combined effects of improved nutrient acquisition, soil structure, and biological activity (Akinnifesi et al., 2010), supporting the idea that targeted P application in nutrient-poor soils can maximise the productivity of agroforestry systems.

* 1. **Crop yield change across topographic variables**

# Recent studies confirm that yield responses to sustainable cropping practices (SCPs) vary with slope, landform and elevation, largely due to differences in soil moisture, erosion, and microclimate. Yield responses varied across slope gradients, with the highest gains on gentle (1–5%, 3.4%) and strong slopes (15–30%, 11%), suggesting moderate slopes enhance SCP performance by improving infiltration and reducing runoff (Wang et al., 2019; Tesfaye et al., 2021). Specifically, agroforestry (AF) was most effective on level to gently sloping areas (<15%) and also in high-elevation areas such as mountain slopes and high plains (>250 m), likely due to stable soil conditions and effective tree-crop interactions (Karki & Goodman, 2021) in combination with improved drainage and reduced erosion (Karki & Goodman, 2021; Poudel et al., 2020). Organic fertilization (OF) also performed well on moderate highland slopes, likely due to enhanced nutrient cycling (Kisinyo et al., 2015). Conservation cropping (CC) showed strong yield gains on both gentle and steep slopes, benefiting from improved erosion control and soil structure (Woldetsadik et al., 2018). Meanwhile, CC and no-till (NT) systems recorded yield increases in lower-elevation landforms like terraces and valley slopes, where they most likely help retain moisture and reduce degradation (Tesfaye et al., 2021; Woldetsadik et al., 2018).

* 1. **Crop yield change across NT management strategies**

Our subgroup analysis of no-tillage (NT) management strategies revealed that the effectiveness of NT is highly dependent on complementary practices. In arid and temperate regions, NT appears to enhance water retention and reduce evaporative losses, contributing to improved crop performance, particularly when integrated with nitrogen input, soil cover, weed control, and crop rotation. This aligns with earlier meta-analyses (Pittelkow et al., 2015; Corbeels et al., 2014) demonstrating that NT systems are most successful in dry climates when paired with residue retention and nutrient management. The reduced gains in continental regions may be attributed to temperature extremes and limited soil biological activity, which can constrain nutrient cycling and residue breakdown (Sun et al., 2020). Meanwhile, the negative yield impacts observed in tropical regions echo findings by Thierfelder and Wall (2012), where high rainfall, pest pressures, and poor residue quality often compromise NT effectiveness. These outcomes reinforce that NT cannot be viewed as a stand-alone solution; its success depends on agroecological context and the presence of synergistic agronomic practices.

* 1. **Publication bias and sensitivity analysis**

Publication bias and sensitivity analyses confirmed the robustness of the findings. The distribution of effect sizes was approximately normal, and Jackknife resampling revealed that the exclusion of individual studies did not significantly alter the overall effect size. A small number of studies produced estimates that fell outside the 95% confidence when removed and might suggest a relatively greater influence on the overall effect size. However, these deviations did not materially alter the statistical significance or overall conclusions of the meta-analysis. Given the large cumulative sample size across all included studies, the influence of any single study is attenuated, and the pooled estimates remain statistically robust as also observed by Shackelford, et al. 61. Therefore, these influential studies were retained in the analysis due to the large cumulative sample size, ensuring that overall conclusions remained valid, as their exclusion is unlikely to meaningfully affect the interpretation or validity of the overall findings.

* 1. **Limitations of the study and future directions**

The results of this study underscore the potential of SCPs to improve crop productivity, particularly in challenging agroecological contexts. However, the variability in response also suggests that context-specific adaptation is crucial. Policymakers and practitioners should consider local soil and climate conditions, as well as crop types, when promoting specific SCPs.

The number and spatial distribution of the studies considered in this study might limit the generalizability of the results to underrepresented regions. The geographic distribution of the NT and OF practices was skewed toward Europe and America. Meanwhile, there was no study for AF in Latin America where actually between 200 and 357 million hectares are devoted to such practice. Most of the studies were dominated by NT compared to the remaining, suggesting it having a higher influence on the pooled results (Fig. 1). However, the split of the results for each of the SCPs help see their individual trend across the factors considered. These observations show the need of a new global data with higher spatial coverage of SCPs, especially for AF, CC and OF.

In addition, yield was the sole outcome metric considered in this study, despite the multifunctional goals of SCPs—including carbon sequestration, biodiversity enhancement, and climate resilience. This narrow focus may miss important trade-offs and co-benefits that could influence adoption decisions. Moreover, the attribution of yield effects to individual SCPs is complicated by the bundling of practices in many studies as seen for different management strategies for NT. For example, there are instances of AF with alley cropping, forest farming, silvopastoralism, riparian forest buﬀers 62-64 while CC species with fibrous root system (e.g. rye-grass, rye and oats) have a higher potential to control soil erosion while those with thick roots (e.g. white mustard and fodder radish) are less effective in that regard65. Consequently, the individual management strategies related to the SCPs may obscure the specific contribution of each practice and warrant further investigation.

**F**ew studies were conducted under extreme weather conditions (e.g., drought, flood), which are increasingly relevant under climate change. As such, the potential of SCPs to buffer crop yields against climate extremes remains an open question. Consequently, further research is needed to unpack the long-term impacts of SCPs on yield stability, soil health, and environmental services, particularly under future climate scenarios.

**Conclusion**

This meta-analysis demonstrates that soil conservation practices can improve crop yields, but outcomes are highly dependent on environmental and management contexts. While agroforestry and cover cropping consistently enhanced yields, particularly in arid and temperate regions, no-tillage and organic farming showed variable or negative yield responses, especially in tropical and continental climates. Yield gains were most evident in low organic carbon and phosphorus-deficient soils, as well as on steeper or elevated landforms—conditions where soil conservation practices likely mitigate key agronomic constraints. The effectiveness of no-tillage systems was notably enhanced when combined with complementary practices such as nutrient inputs and soil cover.

Our findings affirm the potential of soil conservation practices to support sustainable intensification, particularly in marginalized or degraded environments. However, they also caution against a one-size-fits-all approach. Tailored, integrated strategies that align specific practices with local biophysical conditions are essential to optimize yield benefits and ensure successful adoption. Further research is needed to explore long-term outcomes, yield stability under climate extremes, and the broader ecosystem service implications of SCPs beyond yield alone.

Supplementary Table 1: Crop groups

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Crop | Crop group | Crop | Crop group | Crop | Crop  group |
| Corn | Maize | Cassava | V\_F\_others | Onion | V\_F\_others |
| Maize | Maize | Cauliflower | V\_F\_others | Pea | V\_F\_others |
| Sweet corn | Maize | Celery | V\_F\_others | Peach | V\_F\_others |
| Durum wheat | Wheat | Chickpea | V\_F\_others | Pepper | V\_F\_others |
| Spelt wheat | Wheat | Chilli | V\_F\_others | Physic nut | V\_F\_others |
| Wheat | Wheat | Cucumber | V\_F\_others | Pigeon pea | V\_F\_others |
| Rice | Rice | Choy sum | V\_F\_others | Pigweed | V\_F\_others |
| Soybean | Soybean | Citrus | V\_F\_others | Safflower | V\_F\_others |
| Barley | Other cereal | Clover | V\_F\_others | Satsuma mandarin | V\_F\_others |
| buckwheat | Other cereal | Cocoyam | V\_F\_others | Sesame | V\_F\_others |
| Millet | Other cereal | Coriander | V\_F\_others | Spinach | V\_F\_others |
| millet, finger | Other cereal | Cowpea | V\_F\_others | Squash | V\_F\_others |
| Oat | Other cereal | Dandelion | V\_F\_others | Strawberry | V\_F\_others |
| Pearl millet | Other cereal | Dill | V\_F\_others | Sugar beet | V\_F\_others |
| Rye | Other cereal | Eggplant | V\_F\_others | Sugarcane | V\_F\_others |
| Sorghum | Other cereal | Endive | V\_F\_others | Sunflower | V\_F\_others |
| Tef | Other cereal | Fennel | V\_F\_others | Sweet pepper | V\_F\_others |
| Triticale | Other cereal | Fenugreek | V\_F\_others | Sweet potato | V\_F\_others |
| Coffee | Cash crop | Fig | V\_F\_others | Potato | V\_F\_others |
| Cotton | Cash crop | Flax | V\_F\_others | Pulses | V\_F\_others |
| Jute | Cash crop | Garlic | V\_F\_others | pumpkin | V\_F\_others |
| Peanut | Cash crop | Grape | V\_F\_others | Taro | V\_F\_others |
| Tobacco | Cash crop | Green bean | V\_F\_others | Tomato | V\_F\_others |
| African eggplant | V\_F\_others | Hazelnut | V\_F\_others | Turmeric | V\_F\_others |
| Alfalfa | V\_F\_others | Japanese spinach | V\_F\_others | Turnip | V\_F\_others |
| Apple | V\_F\_others | Kidney bean | V\_F\_others | Vetch | V\_F\_others |
| Apricot | V\_F\_others | Kiwifruit | V\_F\_others | Vineyard | V\_F\_others |
| Banana | V\_F\_others | Lentil | V\_F\_others | Watermelon | V\_F\_others |
| Bauhinia trees | V\_F\_others | Lettuce | V\_F\_others | Yam | V\_F\_others |
| Bean | V\_F\_others | Linseed | V\_F\_others | Zucchini | V\_F\_others |
| Beet | V\_F\_others | Lupin | V\_F\_others | Quinoa | V\_F\_others |
| Black gram | V\_F\_others | Melon | V\_F\_others | Radish | V\_F\_others |
| Broad bean | V\_F\_others | Mung bean | V\_F\_others | Rapeseed | V\_F\_others |
| Broccoli | V\_F\_others | Mustard | V\_F\_others | Ribwort plantain | V\_F\_others |
| Cabbage | V\_F\_others | Oil palm | V\_F\_others | Runner bean | V\_F\_others |
| Carrot | V\_F\_others | okra | V\_F\_others |  |  |
|  |  |  |  |  |  |

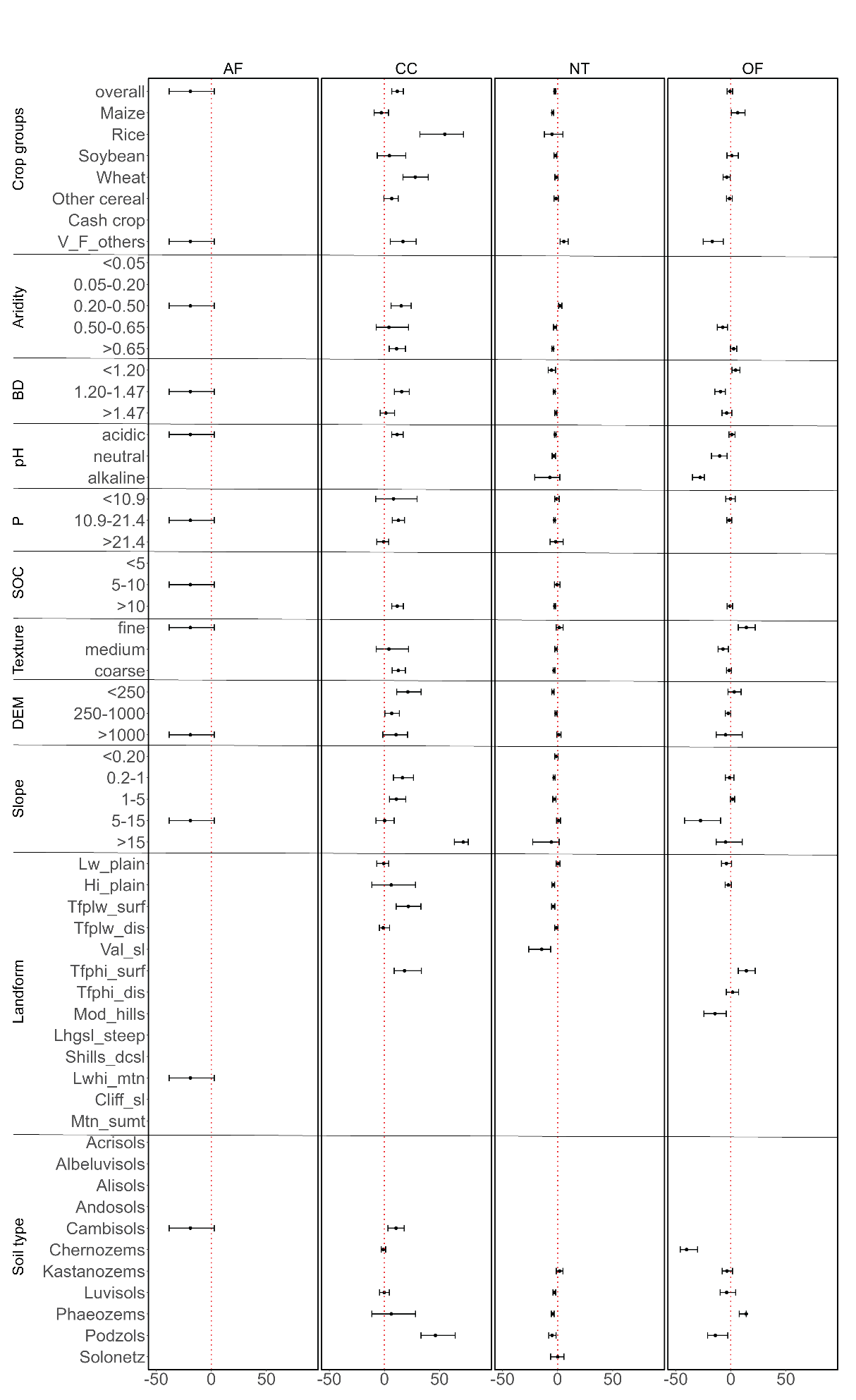
Supplementary Table 2: Summary statistics of the data used in the meta-analysis. AG: agroforestry, CC: cover crop, NT: no-tillage, OF: organic farming. Aridity index are presented as mean (± standard deviation)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop Group | n | Studies | AF | CC | NT | OF | Arid | Continental | Temperate | Tropical | Aridity index |
| Overall | 10 002 | 732 | 783 | 1 029 | 7 622 | 568 | 1 716 | 3 396 | 3 774 | 1 111 | 0.65 (± 0.30) |
| Maize | 3 620 | 314 | 496 | 486 | 2 467 | 171 | 271 | 1 437 | 1 237 | 674 | 0.69 (± 0.25) |
| Wheat | 2 416 | 271 |  | 87 | 2 111 | 218 | 727 | 664 | 987 | 38 | 0.54 (± 0.29) |
| Rice | 486 | 48 |  | 53 | 428 | 5 | 27 | 14 | 338 | 103 | 0.96 (± 0.35) |
| Soybean | 937 | 121 |  | 20 | 899 | 18 | 38 | 561 | 325 | 13 | 0.79 (± 0.21) |
| Cereal | 1 203 | 136 | 169 | 7 | 942 | 85 | 354 | 507 | 313 | 29 | 0.54 (± 0.30) |
| Cash crop | 320 | 37 | 22 | 96 | 198 | 4 | 49 |  | 263 | 8 | 0.78 (± 0.30) |
| Vegetables, fruits and others | 1 020 | 120 | 96 | 280 | 577 | 67 | 250 | 213 | 311 | 246 | 0.58 (± 0.31) |
|  |  |  |  |  |  |  |  |  |  |  |  |

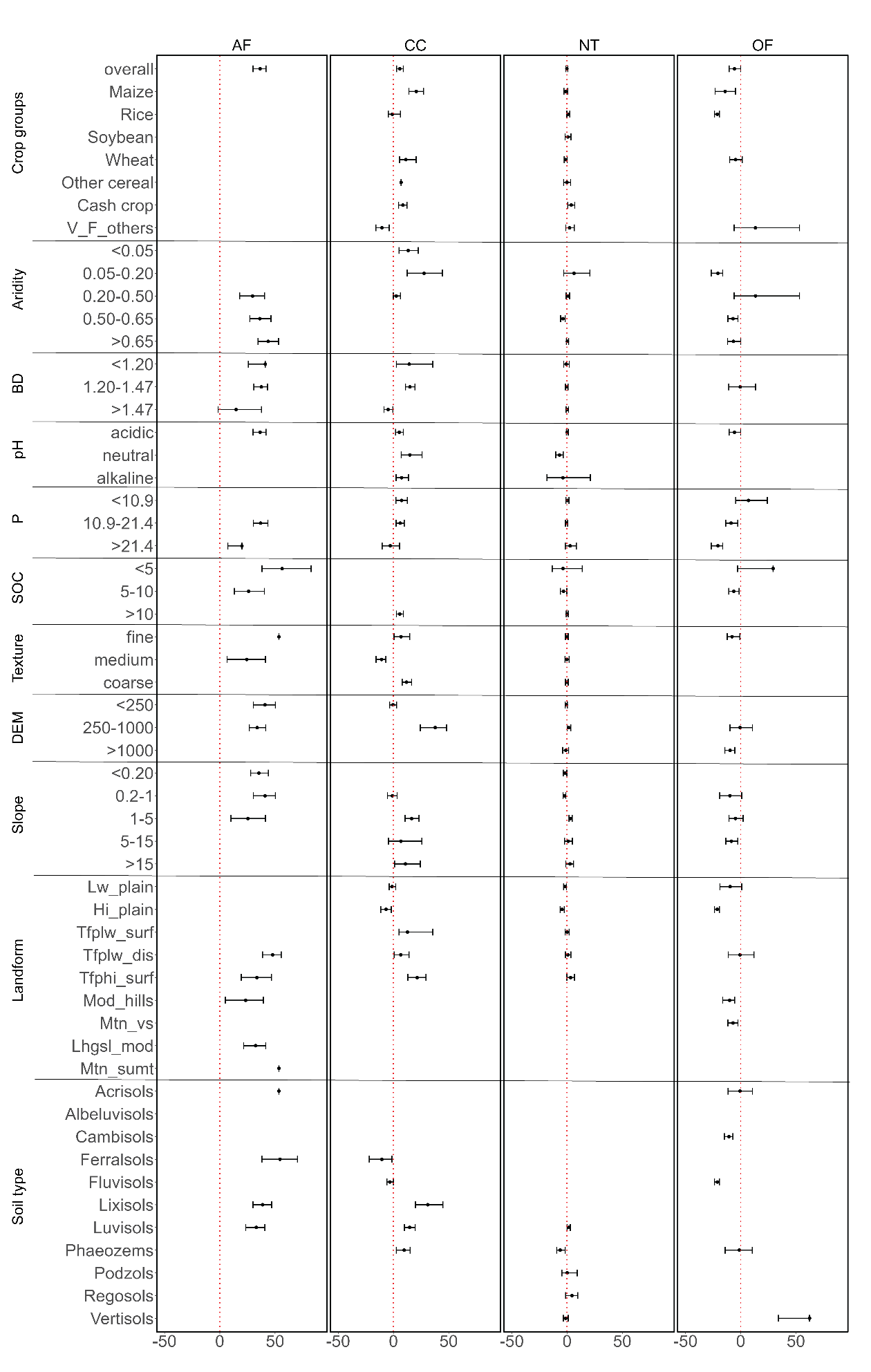
A screenshot of a computer

AI-generated content may be incorrect.

Supplementary material 2: Distribution of effect size for different management practices in the arid zone across different environmental moderator



Supplementary material 3: Distribution of effect size for different management practices in the continental zone across different environmental moderators



Supplementary material 4: Distribution of effect size for different management practices in the temperate zone across different environmental moderators

A screenshot of a computer screen

AI-generated content may be incorrect.

Supplementary material 5: Distribution of effect size for different management practices in the tropical zone across different environmental moderators

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