**Evaluating yield variability in regenerative agriculture: a global analysis across climate, soil, and topography**

Kpade O. L. Hounkpatin1\*, Johannes Piipponen1, Emanuela De Giorgi2, Mika Jalava1, Jeroen Poelert1, Matti Kummu1\*

1. Water and Development Research Group, Aalto University, Espoo, Finland
2. Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy

**Abstract**

Enhancing ecosystem services while supporting sustainable crop production (SCP) is essential, but the impacts of these practices on crop yields are often context-specific and inconsistently reported. In this study, we evaluate how four SCPs—agroforestry (AF), cover cropping (CC), no-tillage (NT), and organic farming (OF)—influence yields compared to conventional tillage. We integrate results from existing meta-analyses with environmental factors, including climate, topography, and detailed soil characteristics, to understand their relative impacts on yield variability across diverse spatial and agronomic conditions. Overall, SCPs increased crop yields by an average of 0.7%, though substantial variation exists among different practices and environmental conditions. Agroforestry and cover cropping provided the largest yield increases (12% and 7.5%, respectively), whereas no-tillage and organic farming slightly reduced yields (-0.7% and -2%, respectively). Yield improvements were most noticeable in arid and temperate climates, soils with low fertility, and areas with elevated or sloping terrains, especially for maize and cash crops. Additionally, management practices strongly influenced the success of no-tillage, with nutrient management and maintaining soil cover identified as critical, particularly in water-limited regions. These findings highlight the necessity of aligning SCPs with local environmental conditions to optimize yields and improve the adoption and effectiveness of regenerative agricultural methods across varied agroecological contexts.

1. **Introduction**

More than 70% of the Earth's land, originally covered by forests and natural ecosystems, has been converted for human use, with agriculture alone accounting for approximately 40% of the global land area. 1. 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. Although there is no clear consensus about a common definition for regenerative agriculture, most concepts center on rebuilding soil quality as a foundation for sustainable production8. In this context, regenerative agriculture involves different soil conservation practices (SCPs) such as reduced or not tillage (NT), cover crop (CC), perennials and agroforestry (AF), organic farming (OF) 6,9. Existing studies report potential beneﬁts of different SCPs for increasing soil organic carbon (SOC) and soil water uptake as well as GHG mitigation climate mitigation 6,9,10. Thus, although environmental benefits seem to be considerable, yield outcomes through the implementation of different SCPs are subject to many controverses.

Yield outcomes under different SCPs have indeed shown mixed results. Some existing studies have shown that implementation of SCPs could potentially result in increasing yields11,12 while others reported a neutral or declining trends13,14. While evaluating the outcome of different crops and environmental variables on NT, as compared to conventional tillage (CT) yields, Pittelkow, et al. 15 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 on 740 paired measurements from 90 peer-reviewed articles show that NT increased barley yield by 49% especially in dry climate16. In a drought period, about 60% higher maize yields were observed under NT management compared to CT17. 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 CT18. The same study showed that OF had 15% lower yield compared to CT.

A similar pattern of context-dependent results is seen with other SCPs like AF and CC. Under AF management, findings show that crop yields either increased by 7 – 16%, especially in subtropical and tropical zones19, or reduced by 2.6% in European areas depending on the density and age of the trees20. While about 14% yield increase is reported under CC especially in coarse soil texture and dryland areas along with the use of leguminous cover crops21, about 3% yield reductions were observed especially for cash crops in temperate soils22,23. About 10% decrease in wheat yields were observed following cover cropping24. In context whereby there is no significant increase or decrease, some studies reported that yields could be sustained for longtime under SCPs especially for degraded soils25. The discrepancy of yield outcomes under different SCPs have thus shown that various factors interplay to determine the magnitude and direction of crop yields for farmers.

Crop yields are influenced by a combination of soil, climate, topography and management practices. For examples, soil properties such as pH, organic carbon content, nutrient levels (e.g. nitrogen, phosphorus), texture, and bulk density directly affect a soil water-holding capacity, root growth, and nutrient availability to plants26-28. Healthier soils with ample organic matter can better support high yields by retaining moisture and supplying nutrients29. Temperature and precipitation regimes play a decisive role in crop productivity. Extreme heat and drought stress can dramatically reduce yields, as evidenced by rising temperatures and more frequent droughts already depressing crop production in many regions30,31. Hence, sufficient rainfall or irrigation, and favorable temperatures during the growing season, are critical for realizing potential yields. The landscape position (elevation, slope gradient, etc.) influences erosion rates, drainage, and microclimates within a field. Steep or elevated fields may lose topsoil and water to runoff, whereas lower or flatter areas can accumulate moisture but risk waterlogging32,33. Even small changes in slope or aspect create different microclimatic conditions (such as cooler hollows or warmer south-facing slopes) that can affect crop growth34.

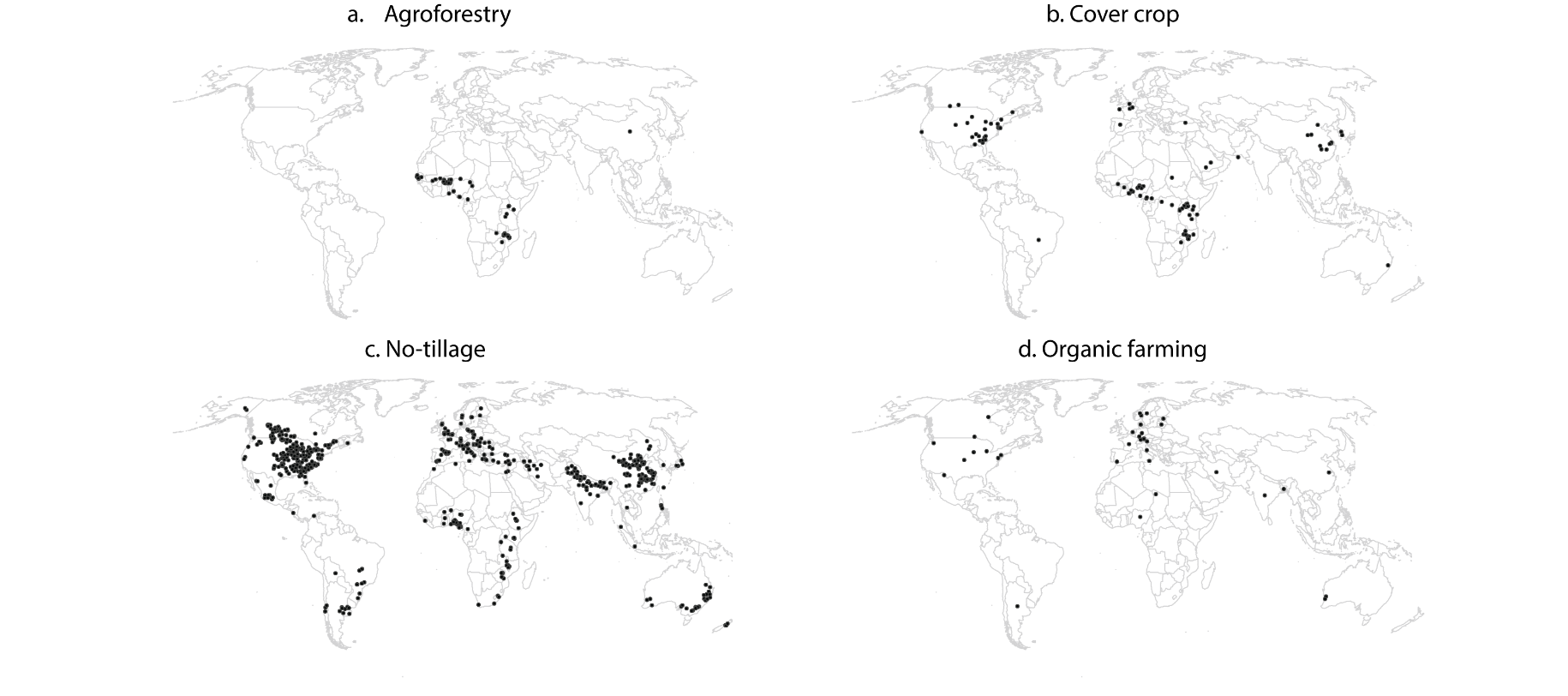
Integrating these environmental factors is crucial for developing tailored, sustainable agricultural systems that optimize crop productivity and environmental benefits. However, field experiments and even many meta-analyses often do not report detailed soil metrics – such as bulk density, soil organic carbon, nutrient availability (e.g. phosphorus levels), pH, texture – nor do they fully capture site characteristics like elevation and slope or climate indices like growing degree-days and seasonal moisture levels. Additionally, previous global comparisons of sustainable farming techniques have usually examined one practice at a time (e.g. only no-till vs. conventional, or only chemical vs. organic inputs) 12,35-37 . Such studies rarely attempt to compare the relative effectiveness of multiple regenerative practices across different environments and crop types simultaneously. This fragmentary approach leaves a significant knowledge gap in relation to how and why yield responses to different SCPs vary under diverse soil and climate conditions. There remains therefore a clear need for a broader understanding of how environmental factors influence crop yield responses under different SCPs.

Notably, recent advances in remote sensing, geospatial modeling, and digital soil mapping now make it possible to fill in many of these data gaps. Global earth datasets can provide information on climate, soil properties and topography virtually anywhere on the planet. For example, climate indicators can be sourced from different platforms at a global scale (e.g. CHELSA38, CHIRPS39, aridity index40 etc.). For soil properties, the SoilGrids database offers gridded global maps of soil attributes (like organic carbon content, texture, pH, etc.) at multiple depths, derived from thousands of soil profiles and environmental covariates41. Meanwhile, the SRTM digital elevation model (at ~30 m resolution) and similar terrain datasets capture fine-scale variations in elevation and slope. Consequently, all these platforms provide information on environmental conditions and variables related to soil properties, climate, topography etc. which in turn are potential factors affecting crop yields42-44. By extracting these variables for the locations of field experiments, it is possible to characterize each site’s environmental context without having had to measure everything on the ground. Leveraging such global data enables large-scale assessments of factors influencing crop yields – essentially allowing us to scale up from individual trial results to broader patterns.

In our study, we capitalize on these developments by combining field trial data with collated global environmental data to evaluate multiple SCPs side by side. Specifically, we gather results from numerous experiments worldwide that compared these practices (like no-till, cover cropping, agroforestry, organic farming) against conventional controls, and for each site we overlay information on climate, soil, and topography drawn from global datasets. This approach allows us to assess how yield responses to different SCPs vary across a wide range of climatic zones, soil conditions, and landscape positions. By analyzing many practices and environmental variables together, our study provides a more comprehensive, comparative perspective on SCP outcomes than previous analyses focused on a single practice. We aim to identify which combinations of practice and environment tend to produce positive yield results, and where trade-offs might occur, thereby offering insights into the contexts in which SCPs can best contribute to both food security and sustainability.

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

We first combined various global meta-analysis data from Xu et al.12, Jian et al.45, Pittelkow et al.35, Xia et al.46, Verret et al.47, Ding et al.48 and Felix et al.36 to create a comprehensive dataset of field scale studies. This resulted in a total of 10 232 comparisons between SCPs 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 1-2 in supplementary material). The compiled data cover the following SCPs practices: Agroforestry (AG), Cover Crop (CC), No-tillage (NT), organic farming (OF).

Figure 1: Global distribution of the study sites

* 1. **Environmental moderators**

The impact of the SCPs on crop yields was assessed based on three environmental components: climate, soil properties and topography. For each of the three components, several indicators were identiﬁed (Table 1).

Climate, topographic and soil properties variables have been documented to have a major impact on crop growth and food production49-52. 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 in 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)53. The Growing Degree (GDD) measures the heat accumulation over the growing season (° C) 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. 40.

Topography attributes interact with weather to affect soil temperature and moisture54,55. Water stress occurs most likely in upslope positions with lower and higher variability in yields compared to lower slope positions56-58. Topographic variables such as elevation and slope (1 km) were obtained via the platform provided by the global study of Amatulli, et al. 59. The landform grid data was sourced from the study of Iwahashi and Yamazaki 60.

Soil properties determine the local environment for crop growth by affecting soil aeration, nutrient cycling and root growth61,62. 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 activity63,64. Global soil properties such as soil texture (sand, silt, clay), bulk density (BD), soil organic carbon (SOC), pH, and soil types were downloaded from the SoilGrids (250 m) platform which is a global soil information system developed by ISRIC – World Soil Information 41. The global stock of soil Olsen phosphorus came from the global study carried out by McDowell et al.65

In addition to assessing broad environmental factors, we specifically investigated additional management variables—cover cropping (yes/no), nitrogen fertilizer application (yes/no), weeding (yes/no), and crop rotation (yes/no)—within the no-tillage (NT) practice. This focus on NT was motivated by data availability. Among SCPs in our database, NT has the largest number of observations with detailed management information. In contrast, other SCPs lacked sufficient data on these management variables to support meaningful subgroup analyses. Therefore, analyzing NT with these additional factors allows us to better understand how specific management decisions within this practice influence yield variability.

To integrate the meta-analysis data with environmental variables, we overlaid spatial datasets of input factors—such as climate, topographic and soil properties from SoilGrids, - available in raster format with the geographic coordinates of the SCPs reported in the meta-studies. Using these coordinates, we extracted corresponding environmental variable values for each observation point. This spatial extraction and data processing were carried out using R software, enabling the linkage of SCP yield data with environmental conditions.

* 1. **Data analysis**

The data analysis focused on the effect size (ES), which reflects the response ratios (RR) of crop yield to these management systems. The ES was assessed by taking the natural logarithm calculated of RR following Luo, et al. 66 : RR = ln(XT/XC) where XT and XC are the yield value under treatment (NT, AG, CC, or OF) and control, respectively. A moderator analysis was conducted to determine the SCPs 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 plants 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)67.
* pH: Three categories were considered: acidic soils (pH < 6.3,) neutral soils (6.3 < pH < 7.4) and alkaline soils (pH > 7.4).
* 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/kg68.
* Soil organic carbon: Three categories were considered: SOC < 5 g/kg, 5 g/kg < SOC < 10 g/kg and SOC > 10 g/kg69.
* Soil texture: soil textures were classified into three broad categories: fine (clay, silty clay loam, clay loam, and sandy clay), medium (silt loam and loam), and coarse (sandy loam and sand), following USDA Soil Taxonomy70 and FAO guidelines71.
* Soil types: Classes of soil types were used as defined on SoilGrid platform (see Table 3 in supplementary material).
* 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)53.
* 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 < 4000°C/y), high heat Stress (4000°C/y < GDD < 6000°C/y)72,73.
* Elevation: The following elevation classes were considered: < 250 m, 250 – 1000 m and > 1000 m.
* Slope: Five slope classes were defined71: < 0.20%, 0.2-1%, 1-5%, 5-15%, and > 15%.
* Landform: The initial 22 landform classes were reduced to 15 by grouping similar contour line classes (see Table 4 in supplementary material).

Using bootstrapping with 1000 resamples of the mean response ratio, 95% confidence intervals were estimated for each category. An ES was considered non-significant if its confidence interval included zero.

Table 1: Environmental variables (in bracket are abbreviations)

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Indicators | Unit | Resolution |
| Climate | Growing degree days for maize (GDD\_maize) | ° C | 0.0083° |
|  | Growing degree days for wheat (GDD\_wheat) | ° C | 0.0083° |
|  | Growing degree days for rice (GDD\_rice) | ° C | 0.0083° |
|  | Growing degree days for soybean (GDD\_soybean) | ° C | 0.0083° |
|  | Aridity index (aridity) |  | 0.0083° |
| 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 |
|  | Soil type |  | 250 m |
| Topography | Slope | % | 0.0083° |
|  | Digital elevation model (dem) | m | 0.0083° |
|  | Geormorphological landform | | 0.0083° |

* 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 SCPs were created to check the distribution of all individual ES in the dataset to check potential publication bias 74,75. Moreover, a sensitivity analysis was carried out using the Jacknife approach to determine the robustness of the analysis76. 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**

# Across the entire dataset, sustainable cropping practices (SCPs) resulted in a modest overall yield increase of 0.7% (Fig. 2). However, responses varied markedly by practice and crop. Agroforestry (AF) and cover cropping (CC) significantly enhanced yields, increasing them respectively by 12% and 7.5%. In contrast, no-till (NT) and organic farming (OF) were associated with yield reductions of 0.7% and 2%. Amongst crops (considering all SCPs), significant yield gains were observed only in maize and cash crops, which increased by 1.7% and 0.7% respectively.

# Across climate types, arid regions showed the greatest yield increase, averaging 3.8%, followed by a 1.8% rise in temperate regions (Fig. 2). This pattern was supported by the aridity index, with mean yield increases of 9% and 2.7% observed in arid (0.05–0.20) and semi-arid (0.20–0.50) zones. In contrast, continental regions experienced a yield decline, while tropical areas showed no significant change. Considerable yield changes across growing degree day (GDD) ranges varied by crop. Maize showed notable increases at 2700–4000 °C (1.9%) and 4000–6000 °C (5.7%). Rice exhibited high yield gains below 800 °C (11.6%) and between 4000–6000 and 6000–10000 °C (2.8% and 2.7%). Soybean yields increased most within 2700–4000 and 4000–6000 °C ranges (1.9% and 5.7%), while wheat showed its largest gains at 800–2700 °C (1.8%) and 6000–10000 °C (3.8%).

# Regarding soil properties, the greatest yield increases were observed in crops grown on low soil organic carbon (SOC) soils (10%), coarse-textured soils (1.76%), and both alkaline (1.38%) and acidic soils (1.24%). Substantial gains also occurred in soils with phosphorus levels below 10.9 mg/kg (1.3%) and between 10.9–21.4 mg/kg (0.5%), as well as in soils with low (<1.20 kg/dm³, 1.05%) or medium bulk density (1.20–1.47 kg/dm³, 1.3%). Conversely, crops grown on neutral soils experienced significant yield declines. Based on soil classification, the most substantial yield increases occurred in Lixisols (18.3%), Arenosols (14.6%), Calcisols (12.7%), Regosols (4.6%), Acrisols (3.7%), Luvisols (2.3%), and Kastanozems (2.9%). In contrast, significant yield reductions were recorded in Alisols (17.5%), Gleysols (11.3%), and Phaeozems (4.3%).

# Significant yield increases were observed at elevations exceeding 250 meters. The distribution of effect sizes (ES) across slope gradients revealed positive yield responses, with the most notable occurring on gentle slopes (1–5%) with a mean yield gain of 3.4%, and on strong slopes (15–30%) with a mean gain of 11%. Gently sloping areas (5–15%) also showed a positive effect, with a mean increase of 0.53%. Yield increases were generally positive across landforms, except in high plains (Hi\_plain), valley slope (Val\_sl), moderate hills (Mod\_hills) —areas typically found at lower elevations. Conversely, the most pronounced yield gains occurred in high-elevation landforms, ranging from mountain valley slope (Mtn\_vs) to the mountain summit (Mtn\_sumt).

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Comments: To be finalized for plots.

Adopt higher resolution. Present plots in the same structure as the components and variables shown Table 1. Make a heading for each component (e.g. soil properties), then below you show the plots of the variables that belong to those components. Structure the text accordingly for the environmental components. Align red line x=0.

Figure 2: Distribution of the percentage change of the effect size between regenerative agriculture practices, crop groups, soil properties, topography, and climatic variables (SCPs: 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**

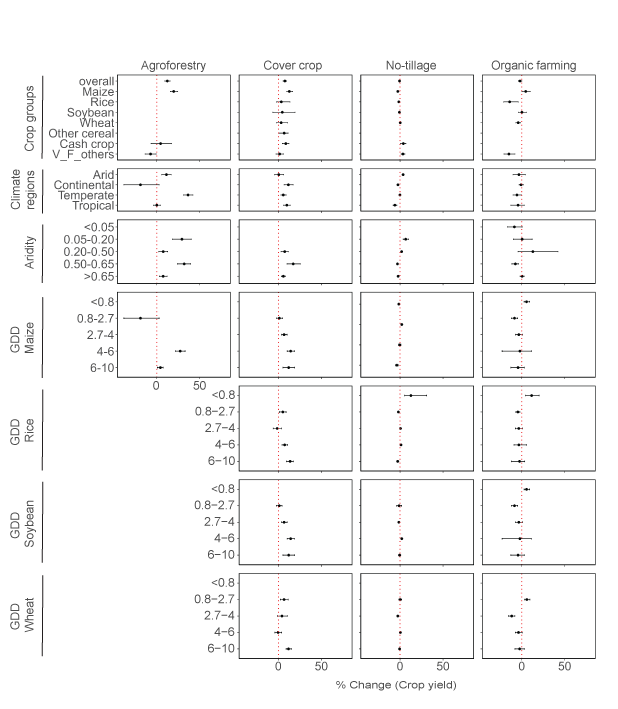
The trend across specific SCPs (Fig. 4) showed that AF recorded a higher yield increase (12%) than CC (7%), NT (-0.7%) and OF (-2%). Cropwise, while most crops have positive mean yield grain under CC the results were mixed for the remaining. Significant yield increase occurred mainly with maize under AF, CC and OF. Similar trend was observed for cash crop under CC and NT. For arid (aridity index: 0.05 – 0.20) and semi-arid (aridity index: 0.20 – 0.50) regions, significant yield increases were observed under AF and NT. Interestingly, most of the positive yield gain obtained under OF occurred also in the semi-arid regions with the 0.20-0.50 aridity index range. AF recorded its highest yield gain in temperate regions (36%). 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°C) resulted in higher yield increase with maize under AF and CC. Meanwhile, significant increase at lower GDD (< 800°C) 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°C under CC. For GDD between 800 and 2700°C, wheat recorded a significant yield increase under CC and OF while above 6000°C GDD, similar tend only occurred with CC. Interestingly, most yield increase for maize, rice and soybean at very low GDD (< 800°C) occurred under OF.

Across the soil properties, 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. All SCPs present high yield increase in soils with low SOC (< 5 g/kg) except OF. However, for soils with higher SOC (> 5 g/kg), AF and CC still recorded high yield increase but in lower magnitude compared to soil with low SOC. Coarse texture soil recorded positive increase across all SCPs except OF but the significant yield records were only found with CC (9%) and NT (3%).

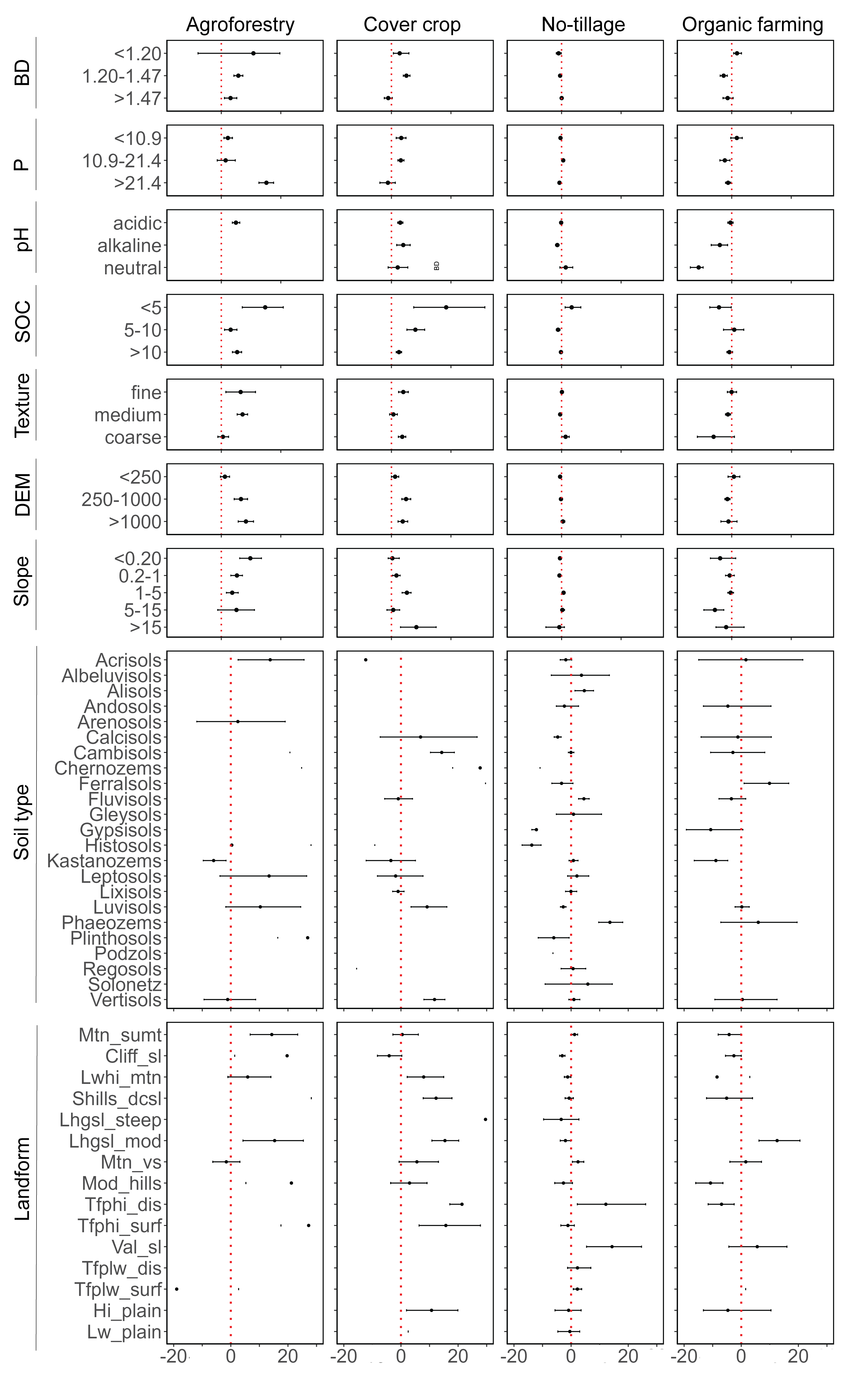
# Considering elevation, significant yield increase was observed for high plain areas above 250 m for both AF and CC. This is further confirmed for these two SCPs by the distribution of the ES across the different landform with generally positive yield increase from the mountain summit to the moderate 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 areas on 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 on the other hand. 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 SCPs 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.

 Comments: To be finalized for plots.

Adopt higher resolution. Present plots in the same structure as the components and variables shown Table 1. Make a heading for each component (e.g. soil properties), then below you show the plots of the variables that belong to those components. Structure the text accordingly for the environmental components. Align red line x=0.

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.



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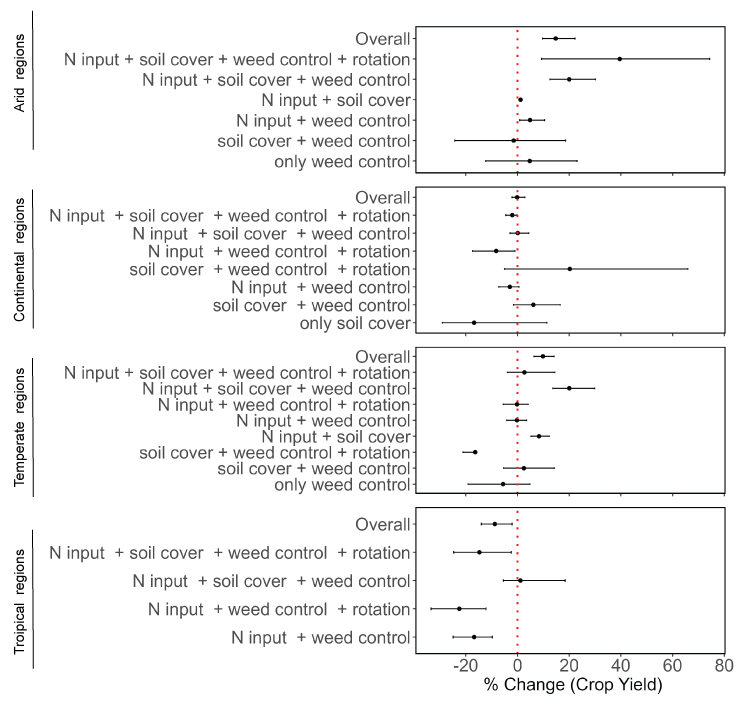
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Figure 4: Distribution of effect size across soil properties and topography between regenerative agriculture practices. P: Phosphorus, BD: bulk density, DEM: digital elevation model**.** , Mtn\_sumt: Mountain summit, Cliff\_sl: Cliff slope, Lwhi\_mtn: 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 different no-tillage management practices**

The effect of no-till (NT) on yield varied across climatic regions and management practices (Fig. 5). Overall, NT implementation led to significant yield increases of 14.7% and 9.8% in arid and temperate regions, respectively, while yield declined in continental (–0.1%) and tropical (–8.7%) regions. The greatest positive impacts of NT were observed in arid zones, particularly under management regimes combining nitrogen input, soil cover, and weed control—with or without crop rotation—yielding increases up to 39%. Other effective combinations in arid regions included nitrogen input with soil cover and weed control (20%), nitrogen input with soil cover alone (1.2%), and nitrogen input with weed control (4.8%). In temperate regions, positive yield gains were noted with nitrogen input combined with soil cover, weed control, and rotation (2.6%), as well as soil cover with weed control (2.5%). The largest increases occurred under management including nitrogen input with soil cover and weed control (20%) as well as nitrogen input plus soil cover (8.3%).

In continental regions, NT resulted in positive yield responses under select management combinations, with increases of 0.09% for nitrogen input with soil cover and weed control, and 6.1% for soil cover with weed control. The greatest gain, 20%, was observed when rotation was added to soil cover and weed control. Conversely, in tropical regions, most NT management strategies resulted in significant yield declines, except for the combination of nitrogen input, soil cover, and weed control, which produced a slight increase of 1.1%.

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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 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 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 large-scale implementation of conservation and soil conservation practices (SCPs) necessitates a comprehensive understanding of the underlying processes and mechanisms influencing crop yield across diverse environmental contexts. While previous studies have documented variable outcomes—including yield increases, decreases, or no significant change—many have not adequately explored the fundamental biophysical and management factors driving these yield responses 11,13,14. However, such knowledge is crucial for context-specific implementation of such practices. This study provides a comprehensive assessment of the impacts of different soil conservation practices on crop yield, considering a broad range of crop groups, climate regimes, soil properties, and topographic characteristics. The overall finding that SCPs associated with regenerative agriculture led to small but significant increases in crop yield, with a pooled average increase of 0.7%, supports growing evidence that sustainable intensification is achievable through SCPs. 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 topographic 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. While these findings align with previous research highlighting the beneficial effects of diversified cropping systems, the magnitude of the effect differs across studies11,21,77. For example, Ren, et al. 11 recorded increased crop yield by 11% and 66% for CC and AF respectively. In contrast, our observed increase for CC is substantially higher than the global average of 2.6% reported by of 2.6% reported by Peng, et al. 21, yet slightly lower than the 9.2% increase reported in cases involving leguminous cover crops, likely due to their nitrogen-fixing abilities. These variations among studies are likely attributable to differences in soil conditions, climate, and management practices. 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 contexts35,78,79.

* 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 SCPs, 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 SCPs especially under AF, CC and OF 19,80. 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 may indicate that these SCPs provide greater benefits in areas with high growing degree days (GDD) compared to conventional practices. This is likely because they enhance soil water retention—through improved drainage and deeper rooting systems, especially in AF—and protect bare soil from direct evaporation of limited precipitation. Additionally, by reducing soil sensitivity to erosion, they improve nutrient retention, making cash crops more resilient during periods of drought and intense rainfall81,82.

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. 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 efficiency83,84. Improved soil structure and moisture retention under organic management can further buffer crops against thermal limitations 85, while reduced pest and disease pressure in cooler climates minimizes reliance on synthetic pesticides. For legumes like soybean, biological nitrogen fixation reduces dependence on external N inputs, favoring thereby organic systems. These findings underscore the importance of agroecological context in assessing the performance of farming systems.

* 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 crops86. 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 conditions15,87, a finding that is especially relevant given the projected expansion of arid zones due to climate change88. 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 losses and leaching are more susceptible.

* 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 activity15,89,90. 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 soils91. 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 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 because it becomes fixed and unavailable to plants. However, its availability is crucial for both plant growth and biological nitrogen fixation, particularly in leguminous tree species commonly found in AF systems92,93. Studies have shown that P inputs can stimulate microbial activity, mycorrhizal associations, and root development, resulting in greater nutrient uptake and biomass production94,95. 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, supporting the idea that targeted P application in nutrient-poor soils can enhance the productivity of agroforestry systems.

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

# Recent studies confirm that yield responses to SCPs vary with slope, landform and elevation, largely due to differences in soil moisture, erosion, and microclimate96,97. Yield responses varied across slope gradients, with the highest gains on gentle (1–5%, 3.4%) and strong slopes (15–30%, 11%) when using the entire dataset, suggesting positive influence of SCPs in improving infiltration and reducing runoff across different gradient of slopes. Specifically, 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 interactions98 in combination with improved drainage and reduced erosion99. OF also performed well on moderate highland slopes, likely due to enhanced nutrient cycling. CC showed strong yield gains on both gentle and steep slopes, benefiting from improved erosion control and soil structure. Meanwhile, CC and NT systems recorded yield increases in lower-elevation landforms like terraces and valley slopes, where they most likely help retain moisture and reduce degradation by stabilizing sediment and organic matter received from upslope. Futerman, et al. 100 reported a 29–58% decrease in rill erosion and corresponding gains in soil structure and infiltration under CC versus bare soil. No-till (NT) combined with terraces cut surface runoff by over 90% and increased moisture storage on valley slopes, stabilizing yields during droughts and intense rains101,102. By trapping upslope sediment and organic matter, CC and NT practices further enrich depositional zones—such as terraces and valley bottoms—with additional nutrients, which supports sustained fertility and productivity.

* 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-analyses15,103,104 demonstrating that NT systems are most successful in dry climates when paired with residue retention and nutrient management. Similarly, the reduced gains observed in continental regions were mitigated when residue retention was implemented alongside weed control and crop rotation.

The impacts of NT on crop yields in tropical regions showed mixed results, with most cases resulting in decreasing yields. This might be attributed to a combination of biophysical and management factors. Tropical soils, often highly weathered and low in structural stability, may suffer from compaction under NT due to reduced soil loosening. This results in delaying seedling emergence and reducing crop vigor105,106 as well as limiting root growth and water infiltration15,107. In humid tropical climates, high residue cover combined with warm, moist conditions can promote the proliferation of pests and diseases, which can further depress yields under NT systems if not properly managed108. In addition, the rapid residue decomposition can reduce the protective benefits of surface residues. This results in agricultural land with inadequate residue cover, which may exacerbate weed competition and reduce moisture conservation, consequently impacting yields103,109. Also, tropical soils often have inherent acidity and low nutrient availability, exacerbating limitations in microbial activity and nutrient cycling under NT systems64. 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.

Despite these challenges, strategic management approaches can mitigate NT-related yield declines in different regions. Studies indicate that integrating NT with complementary practices, such as nitrogen input, cover cropping, and mulching, enhances soil biological activity and improves nutrient availability 110,111. Crop rotation with deep-rooted species further aids in mitigating soil compaction and optimizing nutrient dynamics112. Additionally, long-term NT adoption has shown gradual improvements in soil health and organic carbon retention, which may offset initial productivity losses113. Overall, NT’s effectiveness remains dependent on tailored conservation strategies designed to address regional soil and climatic conditions.

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

Publication bias and sensitivity analyses confirmed the robustness of the findings. The distribution of effect sizes (ES) was approximately normal, and Jackknife resampling revealed that the exclusion of individual studies did not significantly alter the overall ES. 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 ES. However, 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. 114. Consequently, 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 in this study. 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 by policy makers, land managers and farmers. 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 115-117 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 regard118. Consequently, the individual management strategies related to the SCPs may obscure the specific contribution of each practice and warrant further investigation.

This study did not evaluate how different SCPs contribute to the resilience of farming systems under increasingly frequent climate extremes—such as droughts and floods—which is a critical dimension of food security in a changing climate. SCPs might have further potential to buffer yield losses during extreme events but could also bolster farmers’ economic resilience by reducing the risk of total crop failure. Understandably, a modest, stable harvest achieved through enhanced soil health and water management may be preferable to a higher but highly variable yield that collapses under stress. By prioritizing resilience, future studies can explore how SCPs affect long-term yield stability, soil health, and ecosystem services under forecasted climate conditions—and how these advantages translate into more secure and sustainable livelihoods for farmers.

**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. The largest gains occurred under conditions of low soil fertility, high elevation, or significant slope, where these practices likely mitigated structural and nutrient constraints. The effectiveness of no-tillage systems was notably enhanced when combined with complementary practices such as nutrient inputs and soil cover. Our findings highlight the promise of soil conservation practices for sustainable intensification in marginalized or degraded landscapes—but they also warn against blanket solutions. Optimizing yield gains and adoption requires context-specific, integrated strategies that match SCPs to local biophysical conditions and on-the-ground realities. In this light, effective policy could include incentive programs and extension services tailored to regional needs, empowering farmers and land managers to implement the most appropriate SCP combinations. Further research is needed to explore the long-term impacts of SCPs on yield stability during climate extremes and their wider contributions to ecosystem services, which could be framed within the goals of regenerative agriculture and food-security resilience.

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**S**upplementary 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) |
|  |  |  |  |  |  |  |  |  |  |  |  |

Supplementary Table 3: Soil type classes

|  |  |  |  |
| --- | --- | --- | --- |
| Code | Soil class | Code | Soil class |
| 0 | Acrisols | 15 | Kastanozems |
| 1 | Albeluvisols | 16 | Leptosols |
| 2 | Alisols | 17 | Lixisols |
| 3 | Andosols | 18 | Luvisols |
| 4 | Arenosols | 19 | Nitisols |
| 5 | Calcisols | 20 | Phaeozems |
| 6 | Cambisols | 21 | Planosols |
| 7 | Chernozems | 22 | Plinthosols |
| 8 | Cryosols | 23 | Podzols |
| 9 | Durisols | 24 | Regosols |
| 10 | Ferralsols | 25 | Solonchaks |
| 11 | Fluvisols | 26 | Solonetz |
| 12 | Gleysols | 27 | Stagnosols |
| 13 | Gypsisols | 28 | Umbrisols |
| 14 | Histosols | 29 | Vertisols |

Supplementary Table 4: Landform classes

|  |  |
| --- | --- |
| Landform classes | Abbreviation |
| Mountain summit | Mtn\_sumt |
| Cliff slope | Cliff\_sl |
| Lower/hilly mountain | Lwhi\_mtn |
| Steep hills / dissected cliff slope | Shills\_dcsl |
| Large highland slope steep | Lhgsl\_steep |
| Large highland slope moderate | Lhgsl\_mod |
| Mountain valley slope | Mtn\_vs |
| Moderate hills | Mod\_hills |
| Terrace/fan/plateau (high, dissected) | Tfphi\_dis |
| Terrace/fan/plateau (high, surface) | Tfphi\_surf |
| Valley slope | Val\_sl |
| Terrace/fan/plateau (low, dissected) | Tfplw\_dis |
| Terrace/fan/plateau (low, surface) | Tfplw\_surf |
| High plain (Sinks < 50%) | Hi\_plain |
| Low plain (Sinks < 50%) | Lw\_plain |