**Evaluating yield variability in regenerative farming practices: A global analysis across climate, soil, and topography**

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**Abstract**

Enhancing ecosystem services without compromising crop productivity is a central challenge for sustainable agriculture. Yet, yield responses to regenerative farming practices (RFPs) remain highly variable across environments. Here, we synthesized global meta-analyses on four major RFP (agroforestry (AF), cover cropping (CC), no-tillage (NT), organic farming (OF)) and linked field comparisons with spatially explicit climate, soil, and topographic data to identify environmental and management factors driving yield variability. Overall, RFPs produced a modest but significant mean yield increase of 0.8% (with 95% confidence interval, CI: 0.3–1.3%), with large heterogeneity among practices. AF and CC showed consistent benefits (12.3%; 9.3–15.5% and 7.5%; 5.4–9.6%, respectively), while NT (−0.7%; −1.2 to −0.2%) and OF (−2.0%;−3.9 to 0.2%) tended to reduce yields on average. Yield gains were most pronounced in arid and temperate regions, in low-fertility or coarse-textured soils, and at elevated or sloping sites, suggesting that RFPs perform best where soil structure, water retention, or nutrient availability constrain productivity. Sub-analysis of NT, where combinations of NT with nitrogen input, soil cover, weed control, and rotation were analyzed, indicate that yield improvements occurred mainly when nitrogen input, soil cover, weed control, and rotation were applied together, especially under arid climates. These results highlight that yield responses to regenerative practices are context-specific, shaped by interactions between management and environmental conditions. Targeting RFP adoption to locally limiting soil and climate factors can therefore maximize yield potential while advancing sustainable intensification and soil restoration goals.

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 encompasses a range of regenerative farming practices (RFPs) including reduced or no tillage (NT), cover crops (CC), perennials and agroforestry (AF), and organic farming (OF)6,9. Existing studies report potential beneﬁts of different RFPs 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 RFPs are subject to many controverses.

Yield outcomes under different RFPs have indeed shown mixed results. Some existing studies have shown that implementation of RFPs could potentially result in increasing yields11,12 while others reported 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 showed that the impacts of NT on yields is region dependent, with increasing trends observed in moisture-limited arid regions, while declining patterns are found 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 RFPs 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 RFPs especially for degraded soils25. The discrepancy of yield outcomes under different RFPs 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 example, 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-tillage 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 RFPs 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 RFPs.

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. A limitation of this approach is that such variables should ideally be recorded in the field to ensure accuracy and completeness. Nevertheless, leveraging global datasets enables large-scale assessments of factors influencing crop yields, 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 RFPs side by side. Specifically, we gather results from numerous experiments worldwide that compared these practices (like no-tillage, cover cropping, agroforestry, organic farming) against CT 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 RFPs 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 RFP 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 RFPs can best contribute to both food security and sustainability.

1. **Materials and methods**

A global dataset on RFPs was compiled, covering AF, CC, NT, and OF across major crop groups. Each observation was linked with climate, soil, and topographic variables, with additional management information included for no-tillage where available. Yield effects were calculated as log response ratios relative to conventional tillage, and moderator analyses were conducted across environmental categories. Statistical significance was assessed using bootstrapped confidence intervals, while density plots and Jackknife resampling were applied to test for publication bias and robustness.

* 1. **Data collection**

We first combined various global meta-analysis data (Figure 1) 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 10 002 comparisons between RFPs and CT (i.e. conventional tillage) from a total of 906 publications. 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 RFPs: Agroforestry (AF), Cover Crop (CC), No-tillage (NT), organic farming (OF). In line with Jian, et al. 45, we define the four RFPs as follows:

* Agroforestry (AF): trees or shrubs integrated in the same fields with crops and/or pastures, sometimes in combination with (grazing) livestock.
* Cover crops (CC): crops planted in fallow periods, either in rotation or alongside the main crops.
* No-tillage (NT): cropping systems causing minimal or zero soil disturbance through tillage.
* Organic farming (OF): although the exact legal definition of OF varies across nations 49, it relies on using organic fertilizer inputs instead of synthetic fertilizers, such as compost or green manure, and prohibits the application of pesticides.

We acknowledge that some of the four RFPs might be combined in practice, like CC being used as green manure in OF systems. However, in this study we evaluate their yield variability as separate practices.

A map of the world

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Figure 1: Global distribution of the study sites

* 1. **Environmental moderators**

The impact of the RFPs 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 property variables have been documented to have a major impact on crop growth and food production50-53. 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)54. 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 moisture55,56. Water stress occurs most likely in upslope positions with lower and higher variability in yields compared to lower slope positions57-59. Topographic variables such as elevation and slope (1 km) were obtained via the platform provided by the global study of Amatulli, et al. 60. The landform grid data was sourced from the study of Iwahashi and Yamazaki 61.

Soil properties determine the local environment for crop growth by affecting soil aeration, nutrient cycling and root growth62,63. 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 activity64,65. 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.66

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 RFPs in our database, NT has the largest number of observations with detailed management information. In contrast, other RFPs 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 RFPs 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 RFP 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. 67 : RR = ln(XT/XC) where XT and XC are the yield value under treatment (AF, CC, NT, or OF) and control, respectively. A moderator analysis was conducted to determine the RFPs 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 g cm⁻³), moderate (1.2 g cm⁻³ < BD < 1.47 g cm⁻³), high (BD > 1.47 g cm⁻³)68.
* 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⁻¹, moderate: 10.9 mg kg⁻¹ < P < 21.4 mg kg⁻¹ and high: P > 21.4 mg kg⁻¹69.
* Soil organic carbon: Three categories were considered: SOC < 5 g kg⁻¹, 5 g kg⁻¹ < SOC < 10 g kg⁻¹ and SOC > 10 g kg⁻¹70.
* 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 Taxonomy71 and FAO guidelines72.
* 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)54.
* 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), very high heat Stress 6000°C/y< GDD < 10 000°C/y) 73,74, .
* Elevation: The following elevation classes were considered: < 250 m, 250 – 1000 m and > 1000 m.
* Slope: Five slope classes were defined72: < 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. Mean effect sizes (ES) were considered statistically significant when the 95% bootstrapped confidence interval (CI) did not include zero (*p* < 0.05). This criterion follows recent meta-analyses that applied bootstrap resampling to assess significance 11,75.

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⁻¹ | 250 m |
|  | Soil Olsen phosphorus concentrations (phosphorus) | mg kg⁻¹ | 1000 m |
|  | Bulk density (bd) | g cm⁻3 | 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 variance for each study is usually required in meta-analysis to construct funnel plots and perform tests such as Egger’s regression for detecting publication bias76,77. However, most of the primary studies included in this synthesis did not report variance or standard error estimates for yield effects, preventing the application of these conventional approaches. To address this limitation, we examined the distribution of effect sizes (ES) using density plots as a qualitative proxy for funnel plots, assessing potential asymmetry that might indicate publication bias75,78.

# Furthermore, we performed a Jackknife sensitivity analysis analysis79 to test the robustness of the results. Each study was assigned a unique identifier, and data from one study were removed sequentially in each iteration to evaluate the influence of individual studies on the pooled mean of ES. As an additional exploratory check, we inspected potential small-study effects by plotting ES against study sample size to ensure that effect magnitude was not systematically related to study scale. Together, these analyses provided a qualitative yet comprehensive assessment of the robustness and potential bias in the meta-analytic results.

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

# In this section, all crop types were pooled to examine the overall impact of RFPs on yield across different environmental variables. Across the entire dataset, RFPs resulted in a modest but significant overall (Fig. 2) yield increase of 0.8% (with 95% confidence interval, CI: 0.3 to 1.3%). However, responses varied substantially among practices and crop groups. AF and CC significantly enhanced yields by 12.3% (9.3 to 15.5%) and 7.5% (5.4 to 9.6%), respectively. In contrast, NT and OF were associated with slight yield reductions of –0.7% (–1.2 to –0.2%) and –2.0% (–3.9 to 0.2%), respectively. Among crops (considering all RFPs), cash crops increased by 5.3% (3.2 to 7.7%), while maize increased by 0.6% (–0.8 to 2.4%).

# Yield effects also varied across climate zones and temperature regimes. Across climate zones, RFPs produced the highest yield increases in arid and temperate regions, with mean changes of 3.9% (2.6 to 5.2) and 1.8% (1.0 to 2.7), respectively. In contrast, yields declined in continental regions (–1.7%, –2.4 to –1.1) and showed no significant change in tropical regions (+0.4%, –1.3 to 2.5). These patterns were consistent with the aridity index: mean yield increases were greatest under arid conditions (AI = 0.05–0.20; 9.1%, 5.9 to 12.3) and remained positive in semi-arid zones (AI = 0.20–0.50; 2.7%, 1.7 to 3.4). By contrast, yield responses were neutral or slightly negative in sub-humid to humid environments (AI > 0.50). Yield responses across growing degree days (GDD,°C/y) varied by crop. Maize showed notable increases at 2700–4000°C/y and 4000–6000°C/y. Rice exhibited strong gains < 800°C/y, 4000–6000°C/y and 6000–10000°C/y. Soybean increased most within 2700–4000°C/y and 4000–6000°C/y, while wheat showed its largest gains at 800–2700°C/y and 6000–10000°C/y.

# Across soil properties, the largest yield increases occurred in crops grown on soils with low soil organic carbon (SOC) (< 5 g kg⁻¹), coarse texture, and either alkaline or acidic conditions. Substantial gains were also observed in soils with P < 10.9 mg kg⁻¹ and P = 10.9–21.4 mg kg⁻¹ as well as in soils with low BD (< 1.20 g cm⁻³) or medium BD (1.20–1.47 g cm⁻³). Conversely, crops on neutral pH soils experienced yield declines. By soil classification, the greatest mean yield increases occurred in Lixisols, Arenosols, Calcisols, Regosols, Acrisols, Luvisols, and Kastanozems. Yield reductions were recorded in Alisols, Gleysols and Phaeozems.

# Significant yield increases were observed at elevations > 250 m. Positive yield responses were most pronounced on gentle slopes and strong slopes (15–30%). Yield effects were generally positive across landforms, except in high plains, valley slopes and moderate hills. The highest mean yield increases occurred in high-elevation landforms, from mountain valley slopes to mountain summits.

# A chart of crops and crops AI-generated content may be incorrect.

Figure 2: Distribution of the percentage change of the effect size between regenerative agriculture practices, crop groups, soil properties, topography, and climatic variables. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. RFPs: Regenerative farming 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%).

* 1. **Effect size distribution across crops and environmental variables for different soil**

**conservation practices**

In this section, we disentangle how the yield impacts of RFPs vary across practices, crops, climates, soils, and topographic conditions. This allows us to identify where particular RFPs show positive or negative effects and to highlight the environmental and management contexts in which they are most effective.

Cropwise (Fig. 3), most crops exhibited positive mean yield gains under CC, while responses were mixed for other practices. Significant increases were recorded mainly for maize under AF, CC, and OF, and for cash crops under CC and NT. In arid (aridity index = 0.05–0.20) and semi-arid (0.20–0.50) regions, significant yield increases occurred under AF and NT. Notably, many positive yield gains under OF were also concentrated in semi-arid regions. AF recorded its highest yield increase in temperate regions (36%, 95% CI: 30.9 to 42.1%). In more humid zones (aridity > 0.50), higher yield gains were again observed for AF and CC. Yield responses across GDD confirmed that high temperature regimes (> 4000°C/y) resulted in larger yield increases for maize under AF and CC. Significant increases at low GDD (< 800°C/y) were observed for maize under OF and for rice under NT and OF. For rice and soybean, yields increased above 4000°C/y under CC. At moderate GDD (800–2700°C/y), wheat showed significant yield increases under CC and OF, while above 6000°C/y , the positive trend persisted mainly for CC.

# Across soil properties (Fig. 4), yield increased with decreasing bulk density, particularly under AF, CC, and OF. Increasing phosphorus (P) generally increased yield, except at high P (> 21.4 mg kg⁻¹), which resulted in yield declines under CC, NT, and OF. All RFPs showed high yield increases in soils with low SOC (< 5 g kg⁻¹), except OF. For high SOC (> 5 g kg⁻¹), AF and CC still produced positive but smaller yield increases. Coarse-textured soils showed positive mean yield changes across all RFPs except OF, though significance occurred mainly with CC and NT. By soil type, AF produced significant mean yield increases in Acrisols and reductions in Kastanozems. The strongest positive yield responses occurred under CC in Cambisols, Luvisols, and Vertisols, and under NT in Alisols, Fluvisols, and Phaeozems. NT produced negative effects in Calcisols, Gypsisols, Histosols, and Luvisols. OF showed yield increases in Ferralsols and Phaeozems.

# Considering elevation (Fig. 5), significant yield increases occurred above 250 m for AF and CC. This pattern was supported by positive mean effects across landforms ranging from mountain summits to moderate hills. OF showed similar positive trends in areas characterized by large highland slopes (Lhgsl\_mod). Additionally, CC and NT showed significant yield increases in low-elevation landforms. For NT, these increases were observed in dissected terrace/fan/plateau (Tfphi\_dis) and valley slope (Val\_sl) areas, while for CC, significant yield gains occurred in dissected terrace/fan/plateau (Tfphi\_dis), low-surface terrace/fan/plateau (Tfplw\_surf), and high plain (Hi\_plain) regions. For slope, the largest yield increases were observed under AF on level to gently sloping areas (< 15%) and under CC on gentle (1–5%) and strong slopes.

A chart of different crops

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Figure 3: Distribution of effect size across crop groups and climate variables for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. V\_F\_others: Vegetable, fruits and others, GDD (x 1000) : growing degree days.

A chart of different types of soil

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Figure 4: Distribution of effect size across soil properties for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. P: Phosphorus, SOC: soil organic carbon, BD: bulk density.

A diagram of a crop

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Figure 5: Distribution of effect size across topographic variables for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. 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%).

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

NT performance varied strongly across climates and management regimes (Fig. 6). In arid zones, the greatest yield increase occurred with nitrogen input, soil cover, weed control, and rotation (39.6%, with 95% confidence interval, CI: 8.9–71.6%). High gains were also found for nitrogen input with soil cover and weed control (20.0%, 12.4–30.5%) and for nitrogen input with weed control (4.8%, 1.0–10.9%), while other combinations showed high variability and nonsignificant effects. In temperate regions, NT generally improved yields, especially with nitrogen input, soil cover, and weed control (20.0%, 13.9–29.3%) or with soil cover alone (8.3%, 5.3–12.5%). Other combinations yielded modest or nonsignificant changes, whereas weed control alone tended to reduce yields (−5.6%, −18.4–5.2%).

In continental regions, effects were neutral to slightly negative. Nitrogen input with soil cover and weed control had no significant effect (−0.1%, −3.3–4.2%), and adding rotation slightly reduced yields (−2.6%, −4.9–−0.6%). In tropical regions, most combinations led to declines, particularly nitrogen input with weed control (−16.7%, −27.3–−9.9%) and with rotation (−22.5%, −33.7–−12.2%). Only nitrogen input with soil cover and weed control showed a small, nonsignificant increase (1.2%, −5.9–13.2%).

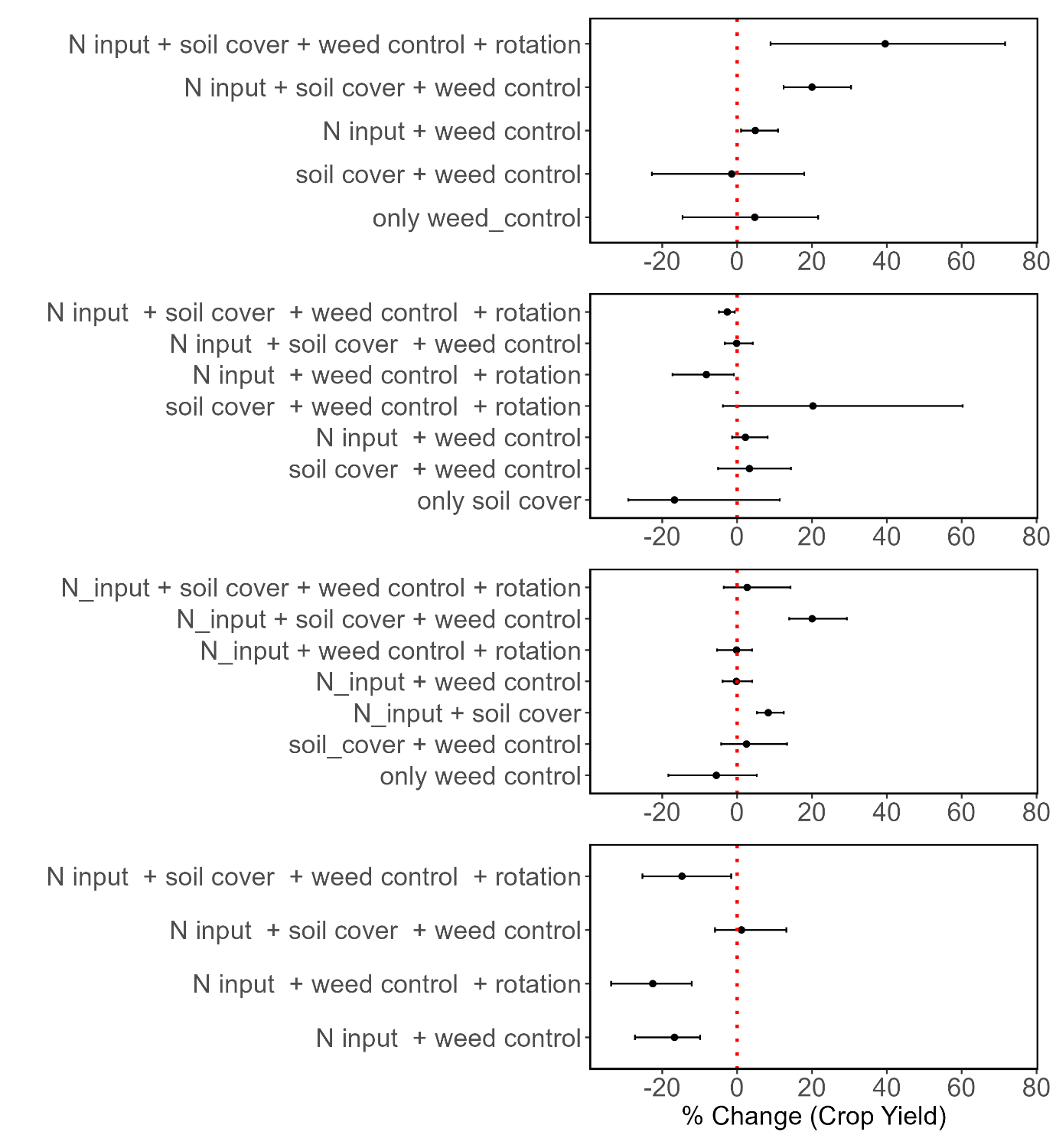
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Figure 6: Distribution of effect size across different no-tillage management practices. N: nitrogen. In brackets are the number of observations per management. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls.

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

The density distribution plot and the histogram show that the observations related to the different RFPS were close to the normal distribution (Fig. 7a,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. 7c).

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# **Figure 7:** 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 RFPs necessitates a comprehensive understanding of the underlying processes and mechanisms influencing crop yield across diverse environmental contexts. While existing 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 RFPs on crop yield, considering a broad range of crop groups, climate regimes, soil properties, and topographic characteristics. The overall finding that RFPs led to small but significant yield increase of 0.8% (95% CI: 0.3 to 1.3%), supports growing evidence that sustainable intensification is achievable through RFPs. 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 significant mean increases of 12.3% (with 95% confidence interval, CI: 9.3 to 15.5%) and 7.5% (5.4 to 9.6%), respectively. While these findings align with previous research highlighting the beneficial effects of diversified cropping systems, the magnitude of the effect differs across studies11,21,80. 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 Peng, et al. 21, yet slightly lower than the 9.2% increase reported in cases involving leguminous cover crops, which is most likely due to their nitrogen-fixing abilities81. 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 (NT (significant decline): mean −0.7%, –1.2 to –0.2%; OF(non-significant decline): mean −2.0%, –3.9 to 0.2%), which may reflect challenges related to nutrient availability, weed pressure, or delayed adaptation of these systems in certain contexts35,82,83.

* 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 RFPs, 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, which are often associated with RFPs, especially under AF, CC and OF 19,84. On the other hand, higher GDD (> 4000°C/y) 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 RFPs provide greater benefits in areas with high growing degree days (GDD) compared to conventional practices. This is likely because AF and CC generally 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 rainfall85,86.

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 efficiency87,88. Improved soil structure and moisture retention under organic management can further buffer crops against thermal limitations 89, while reduced pest and disease pressure in cooler climates minimizes reliance on synthetic pesticides. These findings underscore the importance of agroecological context in assessing the performance of farming systems.

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

Climate context strongly modulated yield outcomes. At the global scale, arid and temperate regions exhibited the largest overall yield increases under RFPs, while continental regions showed modest declines and tropical regions showed no significant change. These patterns align with the aridity gradient, where yield benefits peaked in arid (AI 0.05–0.20) and semi-arid (AI 0.20–0.50) zones and diminished in more humid environments. Such results indicate that RFPs are particularly advantageous under water-limited conditions, where improved soil structure, organic matter, and water retention enhance crop productivity and resilience.

Differences among practices also reflected this climatic gradient produced the greatest yield increases in temperate, continental, and tropical zones, whereas AF and NT performed best in arid environments. The relatively high effectiveness of NT and AF in dry climates likely arises from their ability to conserve soil moisture, reduce erosion, and maintain soil cover—key mechanisms that buffer crops against drought stress. In contrast, CC can be constrained under low-rainfall conditions, as cover crops may compete with main crops for limited water, reducing overall yield90. Consequently, the pronounced benefits of AF and NT in arid areas underscore their value for stabilizing production where conventional methods often exacerbate soil degradation and moisture loss. This further highlight the potential of these practices to enhance resilience and productivity under increasingly dry conditions15,91, a finding that is especially relevant given the projected expansion of arid zones due to climate change92. In humid regions (AI > 0.50), the relative yield advantages of RFPs were smaller, yet AF still achieved notable gains, particularly in temperate climates. These benefits likely reflect improved nutrient cycling, reduced erosion, and enhanced soil structure—functions especially valuable in wetter systems prone to nutrient leaching and runoff. Overall, the observed climatic patterns highlight that the performance of RFPs depends strongly on local water balance and management context. Tailoring the choice of regenerative practice to prevailing moisture regimes can therefore maximize productivity, resilience, and sustainability under both current and future climate conditions.

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

Analysis showed that most of RFPs significantly increased crop yields in soils with low organic carbon (< 10 g kg⁻¹), 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 RFPs 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 activity15,93,94. 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 RFPs except OF, with statistically significant results under CC (mean 9%; median 3%, 25th -9%; 75th23%) and NT (mean 3%; median 0.06%, 25th -10%; 75th12%), consistent with evidence that conservation practices improve water retention and soil structure in sandy soils95. Specificities such as yield reductions in neutral pH soils and high phosphorus soils (> 21.4 mg kg⁻¹) under certain RFPs – 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⁻¹) 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 systems96,97. Studies have shown that P inputs can stimulate microbial activity, mycorrhizal associations, and root development, resulting in greater nutrient uptake and biomass production98,99. Thus, the 38% (median 40%, 25th 12%; 75th69%) 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 RFPs vary with slope, landform and elevation, largely due to differences in soil moisture, erosion, and microclimate100,101. 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 RFPs 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 interactions102 in combination with improved drainage and reduced erosion103. 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. 104 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 rains105,106. 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 NT management strategies confirmed that its effectiveness is highly dependent on complementary practices and local climatic context. Consistent with our quantitative findings (Fig. 6), NT produced the strongest yield benefits in arid and temperate regions when combined with nitrogen input, soil cover, weed control, and crop rotation, with mean yield increases of up to 40% in arid and 20% in temperate climates. Th These combinations likely enhance soil water retention and nutrient availability while minimizing evaporative losses—factors critical in water-limited or moderately dry environments. Such results align with earlier meta-analyses15,107,108 showing that NT performs best under dry conditions when integrated with residue retention and adequate nutrient management. In continental regions, NT effects were mostly neutral to slightly negative, consistent with the small or nonsignificant yield changes observed across management combinations. These moderate responses may reflect shorter adoption periods or limited residue persistence in colder climates, although inclusion of weed control and rotation appeared to partially mitigate yield penalties.

In contrast, NT in tropical regions generally led to yield reductions across most management regimes, particularly when combined with nitrogen input and weed control or with rotation. These negative effects likely stem from several interacting biophysical and management constraints. Highly weathered tropical soils often exhibit low structural stability and are prone to compaction under reduced tillage, which limits root development and water infiltration15,109. Moreover, warm and humid conditions accelerate residue decomposition and favor pest and disease proliferation, reducing the protective and fertility benefits of surface cover110,107,111. Inadequate residue retention and inherent soil acidity further constrain nutrient cycling and microbial activity65, collectively diminishing NT performance.

Nevertheless, targeted management can mitigate many of these constraints. Integrating NT with cover cropping, mulching, or organic amendments can enhance soil structure and biological activity, while rotations with deep-rooted species help alleviate compaction and improve nutrient uptake112,113,114. Over the long term, sustained NT adoption may improve soil organic carbon and structural stability, gradually offsetting early yield declines115. Overall, NT effectiveness is therefore not universal but contingent upon synergistic agronomic practices and the prevailing agroecological setting.

* 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, with no visible asymmetry in the density plots, suggesting the absence of systematic publication bias. Jackknife resampling showed that removing individual studies did not significantly alter the overall ES, indicating stability of the pooled estimates. A few studies produced estimates that fell outside the 95% confidence range when excluded, suggesting they exerted relatively greater influence; however, their impact was minor given the large cumulative sample size across all included studies. This attenuation of single-study influence supports the statistical robustness of the results, consistent with previous large-scale meta-analyses116. These influential studies were therefore retained, as their exclusion would not meaningfully change the overall conclusions.

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

The results of this study underscore the potential of RFPs 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 RFPs.

The number and spatial distribution of the studies included in this analysis may limit the generalizability of the results to underrepresented regions. The geographic coverage of NT and OF studies was heavily skewed toward Europe and North America (Fig. 1), while no AF studies were available from Latin America despite the region hosting between 200 and 500 million hectares117 under such system. Moreover, the dataset was dominated by NT observations compared to the other regenerative farming practices (RFPs), which may have exerted a stronger influence on the pooled results. Although disaggregating results by practice helped reveal individual patterns, these imbalances highlight the need for more globally representative data, particularly for AF, CC, and OF.

In addition, detailed management covariates—such as nitrogen input, soil cover, weed control, and crop rotation—were available only for the NT subset of the dataset. Consequently, management effects could be analyzed exclusively for NT systems, whereas equivalent analyses were not possible for AF, CC, or OF due to limited or inconsistent reporting in the source studies. This introduces a potential selection bias, as NT findings may partly reflect the greater availability of management detail rather than an inherently stronger management–yield relationship. These findings should therefore not be generalized across all RFPs. Future meta-analyses would benefit from harmonized reporting of management variables and broader spatial coverage to enable robust cross-practice and cross-region comparisons.

Another limitation relates to the environmental data used in the analysis. Soil, climate, and topographic variables were derived from global geospatial datasets rather than being measured directly in the field. While these datasets provide valuable standardized coverage at a global scale, they inevitably introduce uncertainty due to potential coordinate inaccuracies in primary studies and spatial scale mismatches between global rasters and plot-level observations118,119. Many meta-analyses report site locations as approximate centroids, which may cause small positional errors when linking field data to environmental covariates120. Moreover, the difference in spatial resolution between global datasets (e.g., SoilGrids 250 m, CHELSA 1 km) and plot-scale trials can result in a modifiable areal unit problem (MAUP), whereby extracted cell averages may not fully represent fine-scale heterogeneity121. For instance, soil properties such as SOC, pH, and bulk density are known to exhibit high spatial variability even within fields, and remote or modeled data may not fully capture this fine-scale heterogeneity122. Similarly, interpolated climate products and DEM-derived terrain attributes may mask microclimatic or field-level differences that strongly affect yield responses123. These uncertainties could influence the precision of environmental relationships identified. Future analyses could mitigate this by testing sensitivity to extraction window size (e.g., 3×3-cell averaging) or by combining global rasters with field-measured variables where available.

In addition, yield was the sole outcome metric considered in this study, despite the multifunctional goals of RFPs—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 RFPs 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 124-126 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 regard127. Consequently, the individual management strategies related to the RFPs may obscure the specific contribution of each practice and warrant further investigation.

This study did not evaluate how different RFPs 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. RFPs 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 failure128. 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 RFPs 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 RFPs 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 regenerative farming 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 regenerative farming practices 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 combinations of regenerative farming practices.

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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 |