Agronomy for Sustainable Development

Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis

--Manuscript Draft--

Manuscript Number:	ASDE-D-25-01720
Full Title:	Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis
Article Type:	Meta-analysis
Keywords:	Regenerative farming practices, yield change, climate, topography, soil property variables
Corresponding Author:	Kpade Ozias Laurentin Hounkpatin, Ph.D Aalto University School of Engineering: Aalto-yliopisto Insinööritieteiden korkeakoulu FINLAND
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Aalto University School of Engineering: Aalto-yliopisto Insinööritieteiden korkeakoulu
Corresponding Author's Secondary Institution:	
First Author:	Kpade Ozias Laurentin Hounkpatin, Ph.D
First Author Secondary Information:	
Order of Authors:	Kpade Ozias Laurentin Hounkpatin, Ph.D
	Johannes Piipponen
	Emanuela De Giorgi
	Mika Jalava
	Jeroen Poelert
	Matti Kummu
Order of Authors Secondary Information:	
Funding Information:	H2020 European Research Council (819202) — Prof Matti Kummu
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% (95% CI: 0.3–1.3%), with large heterogeneity among practices depending on biophysical context. Yield increases were most pronounced in arid and temperate regions, under coarse-textured or low-carbon soils, and at elevated or sloping sites, indicating that RFPs perform best where water and nutrient limitations constrain productivity. Conversely, neutral or negative responses were common in humid or fertile systems, where the relative advantages of RFPs diminish. These results demonstrate that yield responses are governed less by the practice itself than by its alignment with local climatic and soil constraints. Targeting regenerative practices to such limiting environments could therefore maximize both yield potential and ecological benefits, advancing sustainable intensification and soil restoration globally.
Suggested Reviewers:	Ronghua Jian ronghua.jian@usda.gov

	Christian Pittelkow pittelkow@illinois.edu
	Yan Peng yan.peng@purdue.edu
	Bismark K. Adjorlolo b.adjorlolo@csir.org.gh
Author Comments:	

Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis

Kpade Ozias Laurentin Hounkpatin[1]*, Johannes Piipponen[1], Emanuela De Giorgi[2], Mika Jalava[1], Jeroen Poelert[1], Matti Kummu[1]*

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

Cover letter

To the Editors-in-Chief
Agronomy for Sustainable Development

Subject: Submission of manuscript entitled "Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis"

Dear Editors,

We are pleased to submit our manuscript entitled "Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis" for consideration as a Meta-analysis article in Agronomy for Sustainable Development.

Novelty and contribution:
Here we show for the first time, using a globally integrated meta-analysis, how environmental and management factors jointly shape yield responses to key regenerative farming practices (RFPs)—agroforestry, cover cropping, no-tillage, and organic farming—across climatic, soil, and topographic gradients. While previous meta-analyses have focused on individual practices or regional scales, our study combines over 10,000 field comparisons from 906 publications with high-resolution global datasets (SoilGrids, CHELSA, and SRTM). This integration allows us to identify consistent global-scale drivers of yield variability and quantify the contexts where RFPs perform best. The results provide new insight into the environmental determinants of yield outcomes, thereby advancing the design of context-specific sustainable intensification strategies.

Relevance to the journal:
The manuscript aligns closely with the journal's aims to link agricultural practices with sustainability outcomes, demonstrating how regenerative systems can enhance productivity under biophysical constraints. The study provides actionable knowledge for improving soil health, water use efficiency, and resilience to climate variability—key themes for Agronomy for Sustainable Development.

Compliance with the journal format:
The manuscript follows the format required for meta-analyses:
- Title ends with "A meta-analysis".
- Combined Results and Discussion section.
- Clear novelty statements in the abstract, end of the Results and Discussion, and Conclusion.
- Word count under 8000 words (excluding references and figures).
- All declarations (funding, data, code, and authorship) included as required.

Suggested reviewers:
To ensure an objective and expert review, we respectfully suggest the following potential reviewers, all of whom are international experts without conflicts of interest:

1. Dr. Ronghua Jian – USDA Agricultural Research Service, USA – ronghua.jian@usda.gov
2. Prof. Christian Pittelkow – University of Illinois, USA – pittelkow@illinois.edu
3. Dr. Yan Peng – Purdue University, USA – yan.peng@purdue.edu
4. Dr. Bismark K. Adjorlolo – CSIR–Soil Research Institute, Ghana – b.adjorlolo@csir.org.gh

Supplementary material:
We include supplementary tables detailing crop group classifications, soil and landform typologies. This approach avoids inserting lengthy lists of abbreviations into the main text, thereby enhancing readability and maintaining a clear narrative flow.

We confirm that the manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have approved the submitted version and consent to its publication in Agronomy for Sustainable Development.

Thank you for considering our submission. We believe this study provides a significant contribution to the understanding of regenerative farming systems and their role in sustainable food production under varying environmental conditions.

Sincerely,

On behalf of all co-authors
Ozias Hounkpatin

Global determinants of yield variability under regenerative farming practices across climate, soil, and topography: A meta-analysis

Kpade O. L. Hounkpatin[1]*, Johannes Piipponen[1], Emanuela De Giorgi[2], Mika Jalava[1], Jeroen Poelert[1], Matti Kummu[1]*

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 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% (95% CI: 0.3–1.3%), with large heterogeneity among practices depending on biophysical context. Yield increases were most pronounced in arid and temperate regions, under coarse-textured or low-carbon soils, and at elevated or sloping sites, indicating that RFPs perform best where water and nutrient limitations constrain productivity. Conversely, neutral or negative responses were common in humid or fertile systems, where the relative advantages of RFPs diminish. These results demonstrate that yield responses are governed less by the practice itself than by its alignment with local climatic and soil constraints. Targeting regenerative practices to such limiting environments could therefore maximize both yield potential and ecological benefits, advancing sustainable intensification and soil restoration globally.

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, feeding the world has come with a heavy toll on the planet's soils with nearly one-third of agricultural land now shows moderate to severe degradation, threatening long-term food security [2,3]. 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 demand[4]. 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 a collection of alternative farming strategies seeking to achieve global food security by reducing the use of external inputs, improving soil health and minimize environmental damage[5-7]. Although there is no clear consensus about its definition, most concepts center on rebuilding soil quality as a foundation for sustainable production[8]. 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[6,9,10]. Despite promising environmental outcomes, the effects of regenerative farming practices on crop yields remain complex and context dependent.

Yield outcomes under different RFPs have indeed shown mixed results. Some existing studies have shown that implementation of RFPs could potentially result in increasing yields[11,12] while others reported neutral or declining trends[13,14]. Pittelkow, et al. [15] showed that the impacts of NT on yields are context dependent. Yields increased in moisture-limited arid regions but declined 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 climate[16]. In a drought period, about 60% higher maize yields were observed under NT management compared to CM[17]. 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 CM[18]. The same study showed that OF had 15% lower yield compared to CM.

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 zones[19], or reduced by 2.6% in European areas depending on the density and age of the trees[20]. While about 14% yield increase is reported under CC especially in coarse soil texture and dryland areas along with the use of leguminous cover crops[21], about 3% yield reductions were observed especially for cash crops in temperate soils[22,23]. About 10% decrease in wheat yields were observed following cover cropping[24]. 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 soils[25]. 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 plants[26-28]. Healthier soils with ample organic matter can better support high yields by retaining moisture and supplying nutrients[29]. 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 regions[30,31]. 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 waterlogging[32,33]. Even small changes in slope or aspect create different microclimatic conditions (such as cooler hollows or warmer south-facing slopes) that can affect crop growth[34].

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.

To overcome these knowledge gaps, 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. For example, climate indicators can be sourced from different platforms at a global scale (e.g. CHELSA[38], CHIRPS[39], aridity index[40] 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 covariates[41]. Meanwhile, the SRTM digital elevation model (at ~30 m resolution) and similar terrain datasets capture variations in elevation and slope. Consequently, all these data provide information on environmental conditions and variables related to soil properties, climate, topography etc. which in turn are potential factors affecting crop yields[42-44]. By extracting these variables for the locations of field experiments, it is possible to characterize each site's broad environmental context. A limitation of this approach is that such variables should ideally be recorded in the field to ensure accuracy and precision mapping to particular context. Nevertheless, leveraging global datasets enables large-scale assessments of factors associated with crop yields, allowing us to assess broader patterns where data are limited.

In our study, we leverage this approach, combining field trial data with collated global environmental data to evaluate the factors associated with yields for 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 CM 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.

2. Materials and methods

A global dataset on RFPs was compiled, covering AF, CC, NT, and OF across major crop groups (maize, rice, soybean, wheat etc.). Each observation was linked with climate, soil, and topographic variables. Yield effects were calculated as log response ratios relative to conventional management, 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.

2.1. Data collection

We first combined various global meta-analysis data (Figure 1) from the FarmGeek platform (https://www.farmgeek.xyz), which synthesizes peer-reviewed literature on the impacts of agricultural management practices and food system interventions. Key studies drawn from FarmGeek include Pittelkow et al.[35], Xia et al.[45], Verret et al.[46], Ding et al.[47] and Felix et al.[36]. In addition, data from Xu et al.[12] and Jian et al.[48] were incorporated to build a comprehensive, field-scale dataset. This resulted in a total of 10 002 comparisons between RFPs and CM (i.e. conventional management) 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 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. [48], 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.

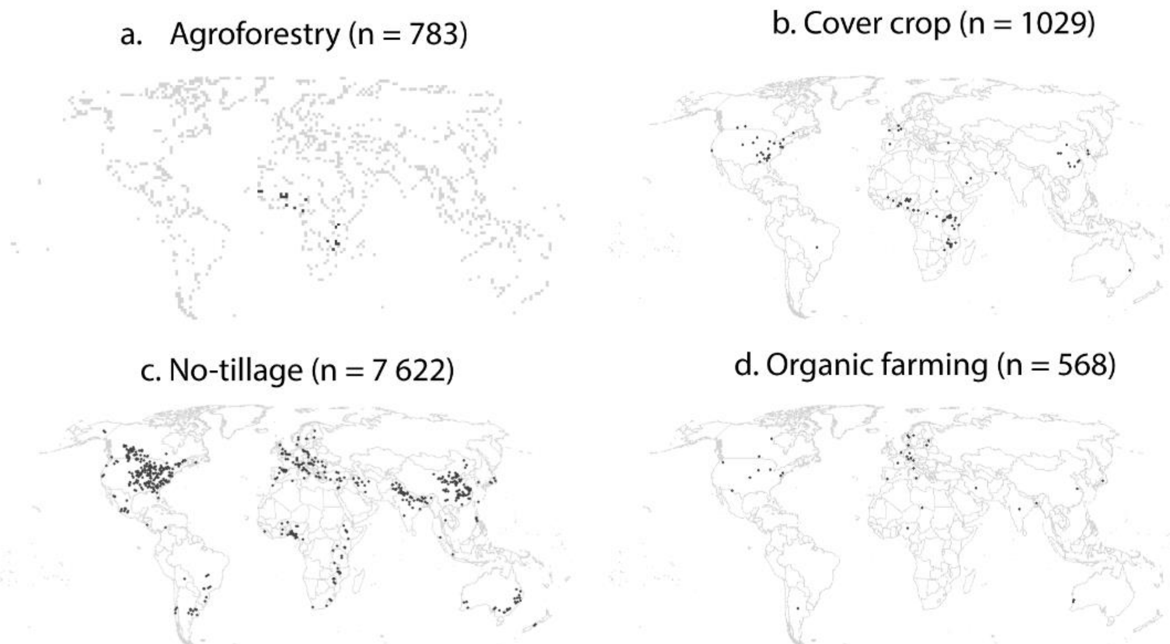

Figure 1: Global distribution of the study sites

2.2. Environmental moderators

The impact of the RFPs on crop yields was conditioned 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 production[50-53]. 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 moisture[55,56]. Water stress occurs most likely in upslope positions with lower and higher variability in yields compared to lower slope positions[57-59]. 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 growth[62,63]. 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 activity[64,65]. 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]

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.

2.3. Data analysis

The data analysis focused on the effect size (ES), which in our case reflects the response ratios (RR) of crop yield to these management systems. The ES was calculated as the natural logarithm of the response ratio (RR) following Luo, et al. [67] : $RR = \ln(X_T/X_C)$ where X_T and X_C 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:

- <u>Crop groups</u>: 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^{-1}[69].
- 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^{-1}[70].
- 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 Taxonomy[71] and FAO guidelines[72].
- Soil types: Classes of soil types were used as defined on SoilGrid platform (see Table 2 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 defined[72]: < 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 3 in supplementary material).

Variance information was unavailable for most primary studies, precluding the use of weighted or random-effects meta-analysis. To estimate the uncertainty around mean response ratios, we therefore applied a nonparametric bootstrap with 1000 resamples drawn at the observation level. The 95% confidence intervals (CIs) were obtained from the empirical percentile distribution of the bootstrapped means, and mean effect sizes (ES) were considered statistically significant when the 95% CI did not include zero ($p < 0.05$). This approach provides descriptive marginal confidence intervals consistent with recent meta-analyses that applied bootstrap resampling to assess significance [11,75] while reducing sensitivity to normality assumptions. However, because within-study dependence and between-study heterogeneity could not be explicitly modeled[76], the results should be interpreted as indicative rather than inferential.

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°

2.4. Publication bias and sensitivity analysis

Given the limited reporting of variance or standard error estimates across primary studies, conventional tests for publication bias (e.g., Egger's regression or funnel plots) could not be applied[77,78]. 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 bias[75,79].

Furthermore, we performed a Jackknife sensitivity analysis[80] 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.

3. Results and discussion

The large-scale implementation of RFPs necessitates a comprehensive understanding of the underlying processes and mechanisms influencing crop yield across diverse environmental contexts. Although existing studies have reported a range of outcomes, such as yield increases, decreases, or no significant change, many have not thoroughly examined the underlying biophysical and management factors that influence 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.

3.1. Crop yield change across practices

Across the entire dataset, RFPs (Fig. 2) resulted in a modest but significant overall (Fig. 2) yield increase of 0.8% (with 95% confidence interval, CI: 0.3 to 1.3%), thereby supporting growing evidence that sustainable intensification is achievable through RFPs. However, the magnitude and direction of yield responses varied considerably depending on the specific practice.

AF and CC significantly enhanced yields by 12.3% (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 studies[11,21,81]. 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 abilities[82]. 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 contexts[35,83,84].

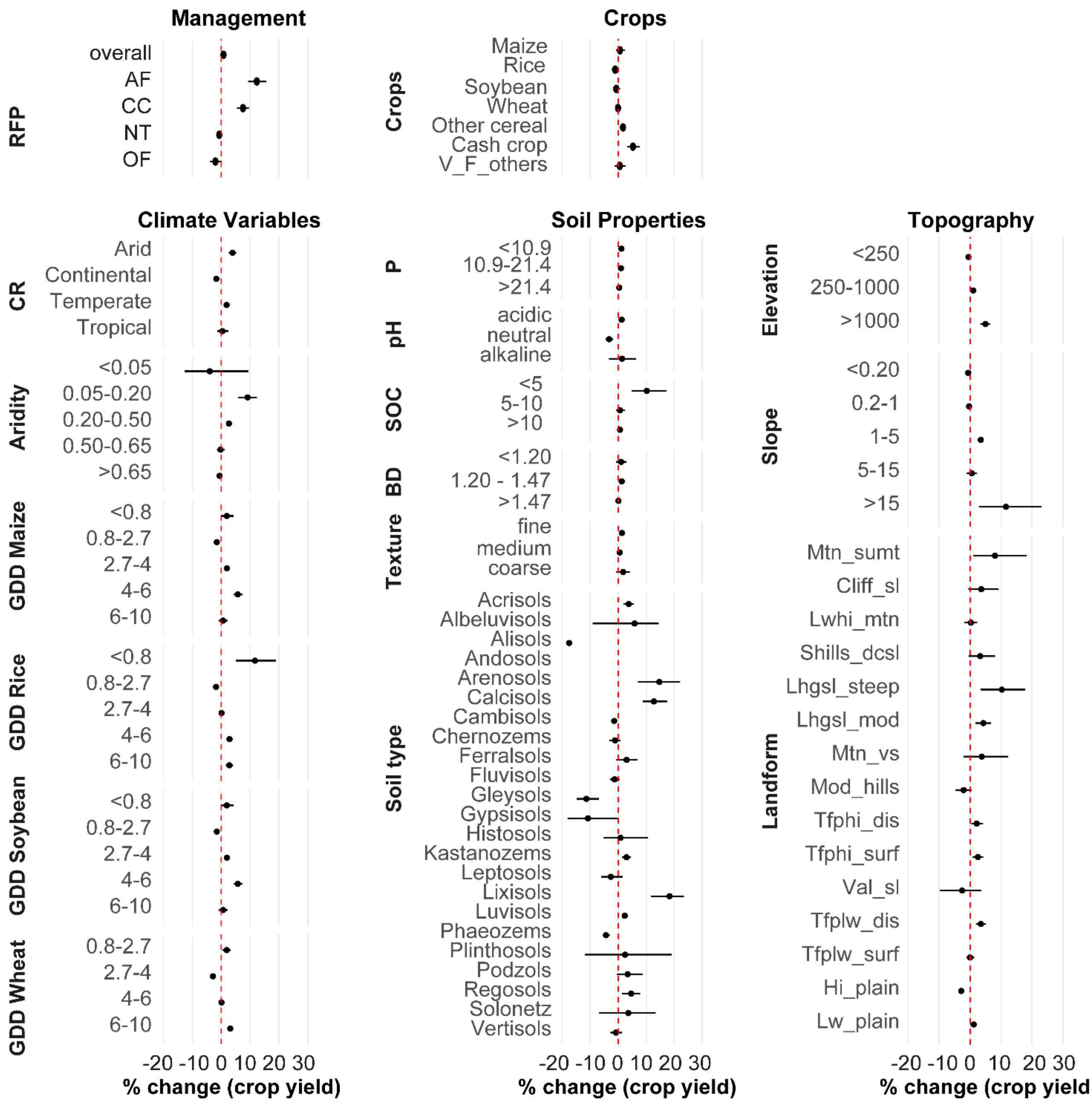

Figure 2: Distribution of the percentage change of the effect size between regenerative agriculture practices, crop groups, soil properties, topography, and climatic variables. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from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

3.2. Crop yield change across climate types

Yield effects varied across climate zones and temperature regimes. Across climate zones (Fig. 2), RFPs produced the highest yield increases in arid (3.9%; 95% CI: 2.6 to 5.2) and temperate (1.8%; 95% CI: 1.0 to 2.7) regions, whereas yields declined in continental regions (–1.7%; 95% CI: –2.4 to –1.1) and showed no significant change in tropical regions (+0.4%; 95% CI: –1.3 to 2.5). These patterns were consistent with the aridity index, with mean yield increases being greatest under arid conditions (AI = 0.05–0.20; 9.1%; 95% CI: 5.9 to 12.3) and remaining positive in semi-arid zones (AI = 0.20–0.50; 2.7%; 95% CI: 1.7 to 3.4). In contrast, yield responses were neutral or slightly negative in sub-humid to humid environments (AI > 0.50). 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. Among practices (Fig. 3), AF and NT showed significant yield gains in arid and semi-arid climates, while many positive OF responses were also concentrated in semi-arid regions. AF achieved its peak yield increase in temperate regions (36%; 95% CI: 30.9 to 42.1), and in more humid zones (AI > 0.50), higher yield gains were again observed for AF and CC.

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, which are essential mechanisms for protecting crops from 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 yield[85]. 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 conditions[15,86], a finding that is especially relevant given the projected expansion of arid zones due to climate change[87]. 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, which are particularly valuable in wetter systems that are susceptible 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.

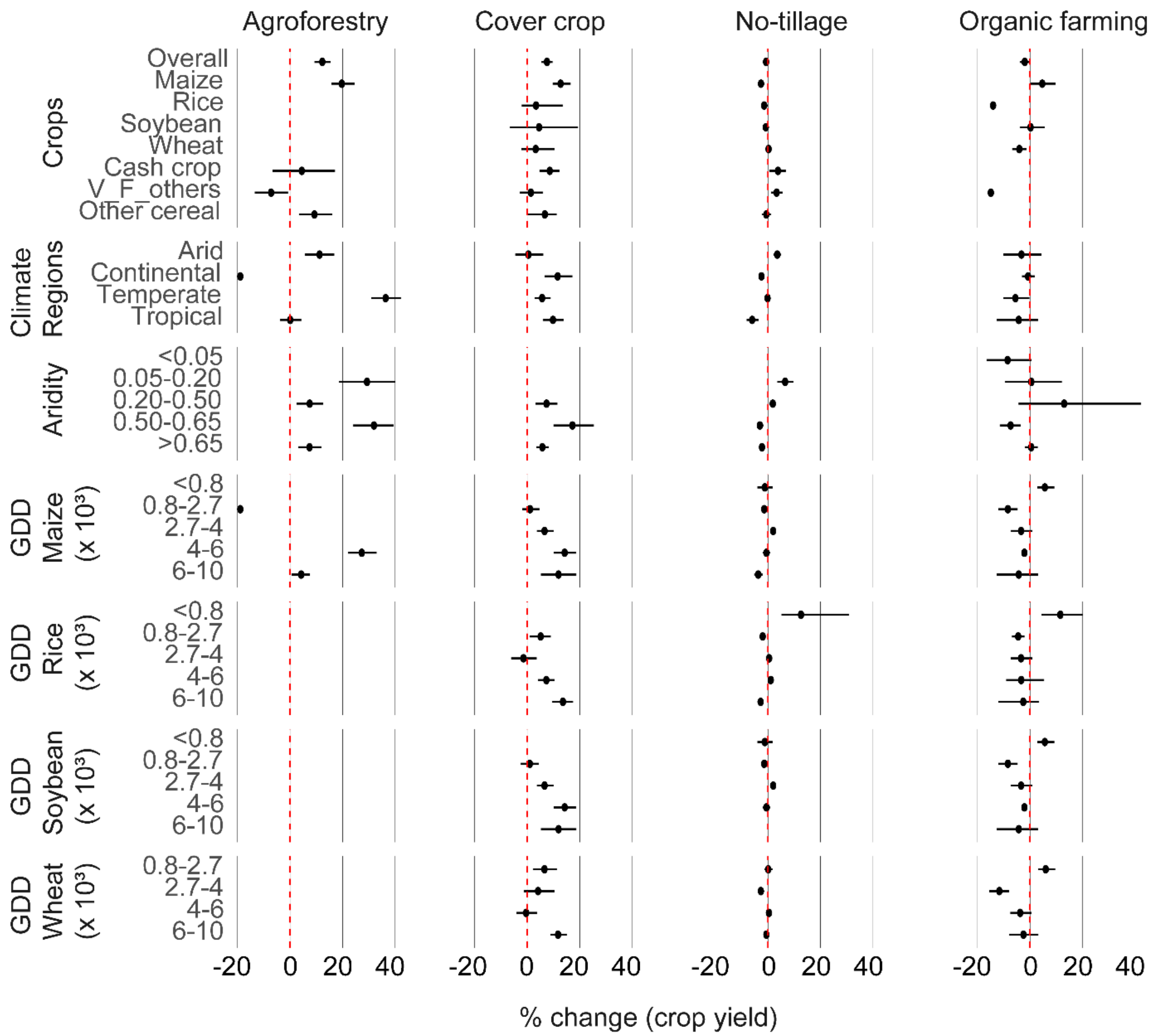

Figure 3: Distribution of effect size across crop groups and climate variables for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. V_F_others: Vegetable, fruits and others,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

3.3. Crop yield change across specific crops and growing degree days

Yield responses to RFPs showed strong variation both among crop types and across thermal regimes, reflecting the interaction between crop physiology, management, and climatic conditions (Figs. 2–3).

Across all RFPs, yield responses varied substantially among crop types. Considering all RFPs (Fig. 2) together, cash crops increased by 5.3% (3.2–7.7%) and maize by 0.6% (–0.8 to 2.4%) while other crop types exhibited mixed responses. Practice-wise (Fig. 3), most species exhibited positive mean yield gains under cover cropping (CC), whereas responses were more variable for other practices (Fig. 3). Significant increases were recorded mainly for maize under AF, CC, and OF, and for cash crops under CC and NT. These findings indicate that maize and cash crops benefited most from RFP adoption, though the extent of yield improvement depended on the practice applied. The higher gains under CC, AF, and OF suggest that practices enhancing soil cover and organic inputs are more effective than disturbance-reducing measures alone. Such practices improve soil structure, water retention, and nutrient cycling, thereby creating favorable conditions for high-input crops that rely on sustained nutrient and moisture supply especially for maize[19,88]. In contrast, the variable performance under NT may reflect slower soil fertility buildup and residue-related constraints, which can limit yield benefits in the short term.

Yield responses across growing degree days (GDD, °C y^{-1}) further revealed strong temperature-dependent patterns. Across all RFPs (Fig. 2), maize showed notable increases at 2700–4000°C y^{-1} and 4000–6000°C y^{-1}, rice exhibited strong gains at < 800°C y^{-1}, 4000–6000°C y^{-1}, and 6000–10000°C y^{-1}, soybean increased most within 2700–4000°C y^{-1} and 4000–6000°C y^{-1}, and wheat showed its largest gains at 800–2700°C y^{-1} and 6000–10000°C y^{-1}. At the RFP level (Fig. 3), high GDD regimes (> 4000°C y^{-1}) resulted in larger yield increases for maize under AF and CC, while low GDD (< 800°C y^{-1}) favored higher yields for maize under OF and for rice under NT and OF. For rice and soybean, yields increased above 4000°C y^{-1} under CC, and for wheat, significant gains occurred under CC and OF at 800–2700°C y^{-1}, with positive trends persisting above 6000°C y^{-1}, mainly under CC. These results demonstrate that temperature regimes modulate the effectiveness of RFPs, with AF and CC performing best in warmer conditions. This is likely because AF and CC generally enhance soil water retention through improved drainage and deeper rooting systems, particularly in AF, and help 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 rainfall[89,90].

Conversely, the strong yield responses to OF under cooler conditions (< 800°C y^{-1}) 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 efficiency[91,92]. Improved soil structure and moisture retention under organic management can further buffer crops against thermal limitations [93], 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.

3.4. Crop yield change across soil properties

Yield responses RFPS varied markedly across soil properties (Fig. 2,4). When all RFPs were pooled (Fig. 2), the largest yield increases occurred in crops grown on low soil organic carbon (SOC < 5 g kg^{-1}), coarse-textured, and acidic or alkaline soils. Substantial gains were also observed in soils with low to moderate phosphorus levels (P < 21.4 mg kg^{-1}) and low to medium bulk density (BD < 1.47 g cm^{-3}), whereas crops on neutral pH soils tended to experience yield declines.

Across individual RFPs (Fig. 4), yield increased with decreasing bulk density, particularly under AF, CC, and OF. All RFPs except OF produced substantial yield gains in low-SOC soils, while under high-SOC conditions (> 5 g kg^{-1}), AF and CC maintained smaller yet positive responses, indicating diminishing returns also in more fertile environments. These findings suggest that RFPs are particularly effective in nutrient-poor or structurally constrained soils, where enhancements in soil structure, nutrient cycling, and biological activity deliver the greatest yield benefits[15,94,95].

Soil texture and classification further influenced the magnitude of yield responses. Coarse-textured soils showed positive mean yield changes across all RFPs except OF, with significant effects under CC, supporting previous evidence that conservation practices enhance water retention and aggregation in sandy soils[96]. By soil type, the greatest mean yield increases were recorded in Lixisols, Arenosols, Calcisols, Regosols, Acrisols, Luvisols, and Kastanozems, while Alisols, Gleysols, and Phaeozems showed declines (Fig. 2). Within this pattern, AF produced notable gains in Acrisols, CC in Cambisols, Luvisols, and Vertisols, NT in Alisols, Fluvisols, and Phaeozems, and OF in Ferralsols and Phaeozems (Fig. 4), indicating that specific practices interact differently with local soil constraints such as drainage, mineralogy, or nutrient availability. Consistent with the climate analysis, AF and CC showed the strongest responses in coarse-textured soils typical of arid environments, reinforcing their role in improving soil water retention and stability under dry conditions.

Increasing phosphorus availability generally enhanced yield, although high P (> 21.4 mg kg^{-1}) resulted in yield declines under CC, NT, and OF, suggesting reduced relative benefits in already fertile systems. Conversely, AF systems sustained yield increases even at high phosphorus levels (> 21.4 mg kg^{-1}). This 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 systems[97,98]. Studies have shown that P inputs can stimulate microbial activity, mycorrhizal associations, and root development, resulting in greater nutrient uptake and biomass production[99,100]. Thus, the 38% (31.6-43.9%) 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 AF systems.

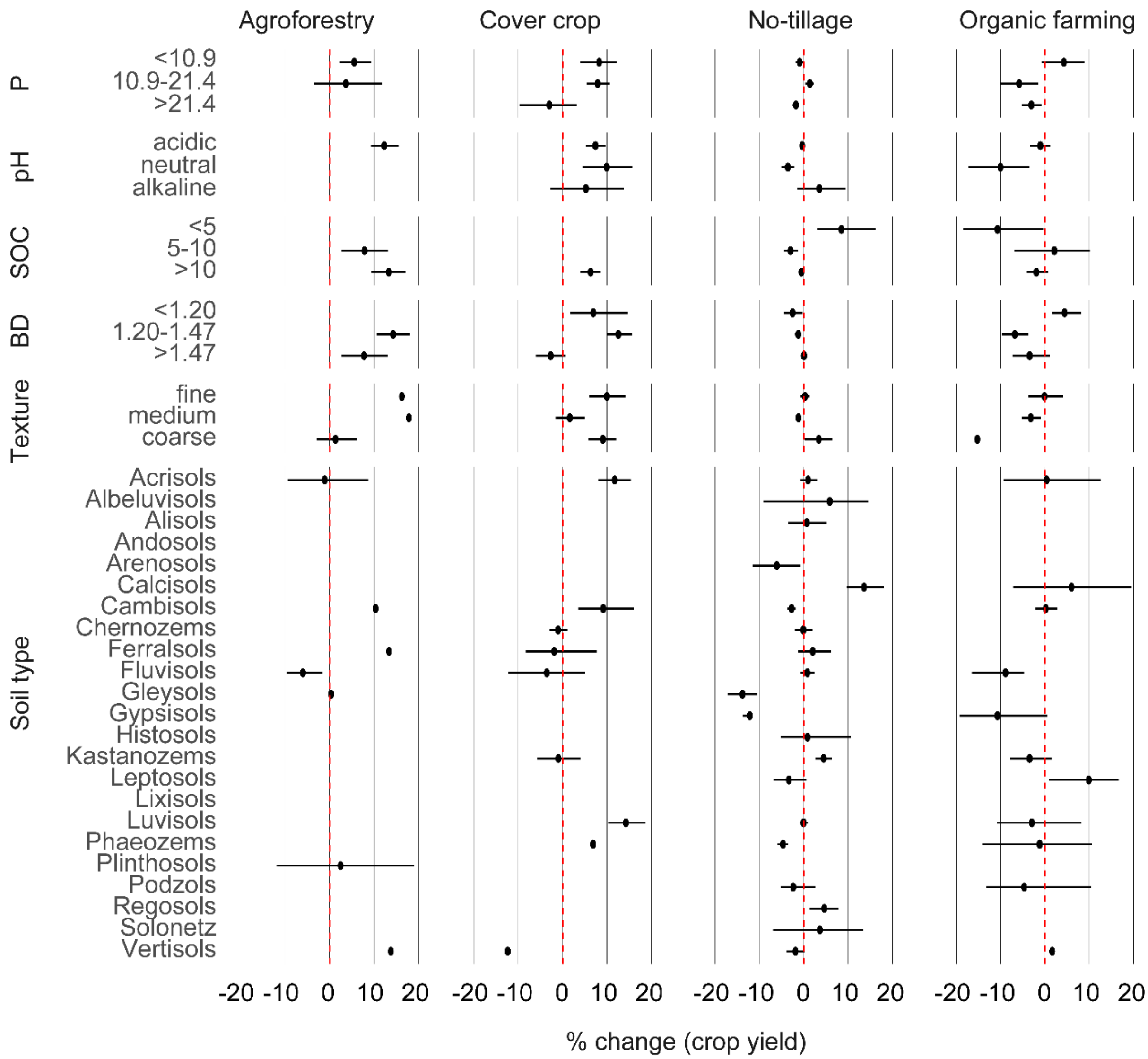

Figure 4: Distribution of effect size across soil properties for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. P: Phosphorus, SOC: soil organic carbon, BD: bulk density.

3.5. Crop yield change across topographic variables

Yield responses to RFPs varied significantly with topographic conditions, including elevation, slope, and landform (Fig. 2,5). When all RFPs were pooled (Fig. 2), significant yield increases were observed at elevations > 250 m, with the highest mean yield gains recorded in high-elevation landforms ranging from mountain valley slopes to mountain summits. Yield effects were generally positive across landforms, except in high plains, valley slopes, and moderate hills, while gentle (1–5%) and strong slopes (15–30%) exhibited the most pronounced yield improvements. These findings align with earlier studies demonstrating that yield responses to RFPs are strongly modulated by topographic gradients due to variations in soil moisture, erosion risk, and microclimate[100,10]. The consistent yield gains on gentle (1–5%, +3.4%) and strong slopes (15–30%, +11%) across the dataset indicate that RFPs improve infiltration, reduce runoff, and stabilize soil productivity under diverse slope conditions.

At the level of specific RFPs, AF was most effective on level to gently sloping areas (< 15%) and also in high-elevation areas such as mountain slopes and high plains (> 250 m), likely due to stable soil conditions and effective tree-crop interactions[101] in combination with improved drainage and reduced erosion[102]. 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.

In lower-elevation landscapes, CC and NT systems also resulted in significant yield increases, particularly within dissected terrace/fan/plateau (Tfphi_dis), low-surface terrace/fan/plateau (Tfplw_surf), and high plain (Hi_plain) regions for CC, and within valley slopes (Val_sl) and dissected terraces for NT. These patterns suggest that both practices effectively conserve moisture and prevent degradation by stabilizing sediment and organic matter in depositional zones. Evidence from field experiments supports this mechanism: Futerman, et al. [103] reported a 29–58% decrease in rill erosion and corresponding improvements in soil structure and infiltration under CC compared with bare soil. Likewise, NT combined with terrace systems has been shown to reduce surface runoff by over 90%, enhancing moisture storage and stabilizing yields during droughts and intense rainfall events s[104,105]. By trapping upslope sediment and organic matter, CC and NT further enrich valley bottoms and terraces with nutrients, sustaining fertility and long-term productivity.

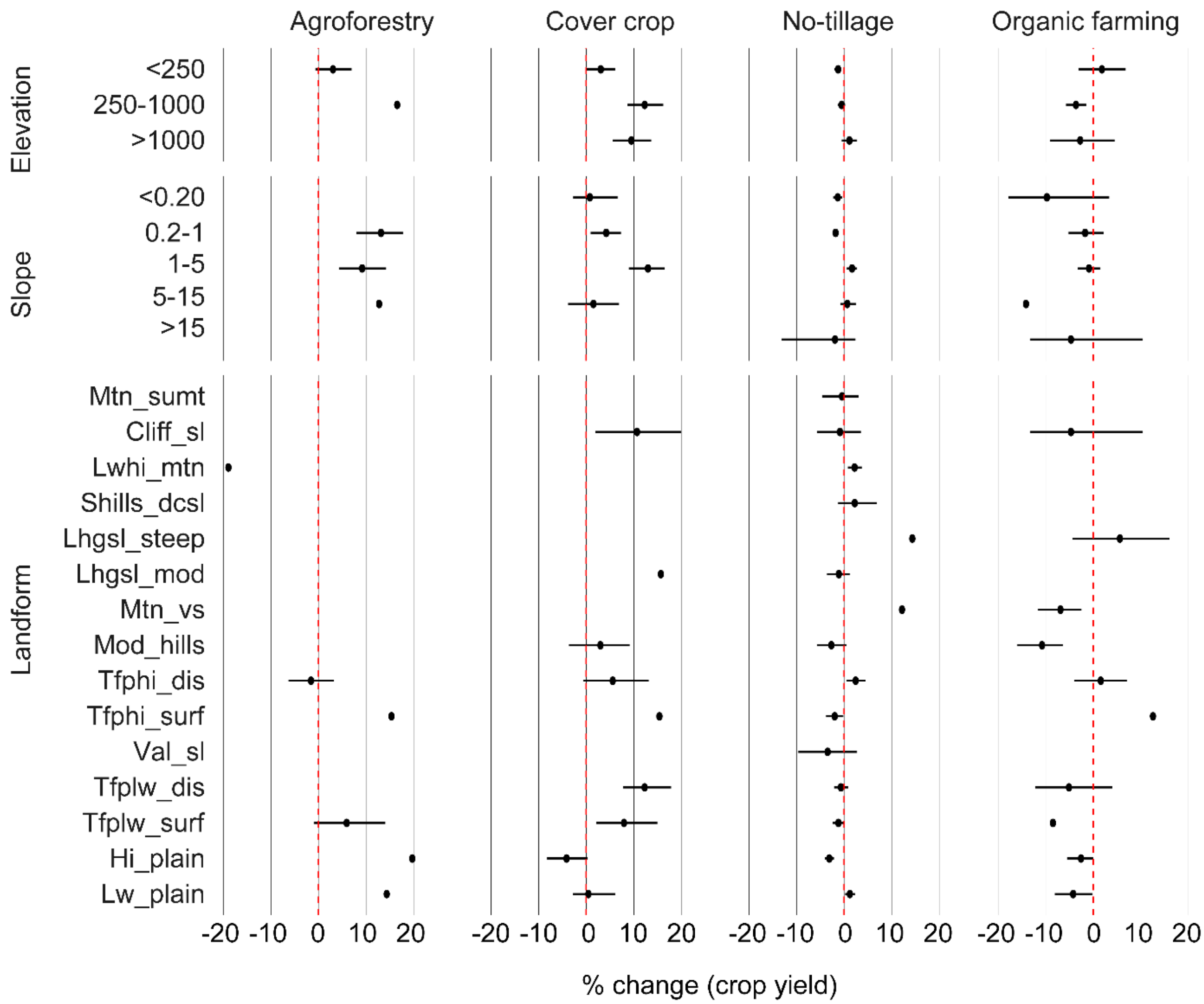

Figure 5: Distribution of effect size across topographic variables for different regenerative agriculture practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) differ significantly from controls. Mtn_sumt: Mountain summit, Cliff_sl: Cliff slope,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

3.6. Publication bias and sensitivity analysis

Density and histogram plots (Fig. 6a,b) indicated that effect sizes were approximately normally distributed, with no visible asymmetry suggesting substantial publication or reporting bias. Similarly, the Jackknife sensitivity analysis revealed that the exclusion of individual studies did not substantially alter the pooled effect size, as most of the recalculated estimates remained within the original 95% confidence interval (Fig. 6c). These findings confirm the robustness and stability of the meta-analytic estimates. Although a few studies produced estimates that fell outside the 95% confidence range when excluded, their influence was minor given the large cumulative sample size and broad representation of experimental conditions. This attenuation of single-study effects underscores that no individual dataset unduly biased the overall results, consistent with findings from previous large-scale meta-analyses assessing the reliability of regenerative practice impacts[106]. Consequently, these influential studies were therefore retained, as their exclusion would not meaningfully change the overall conclusions.

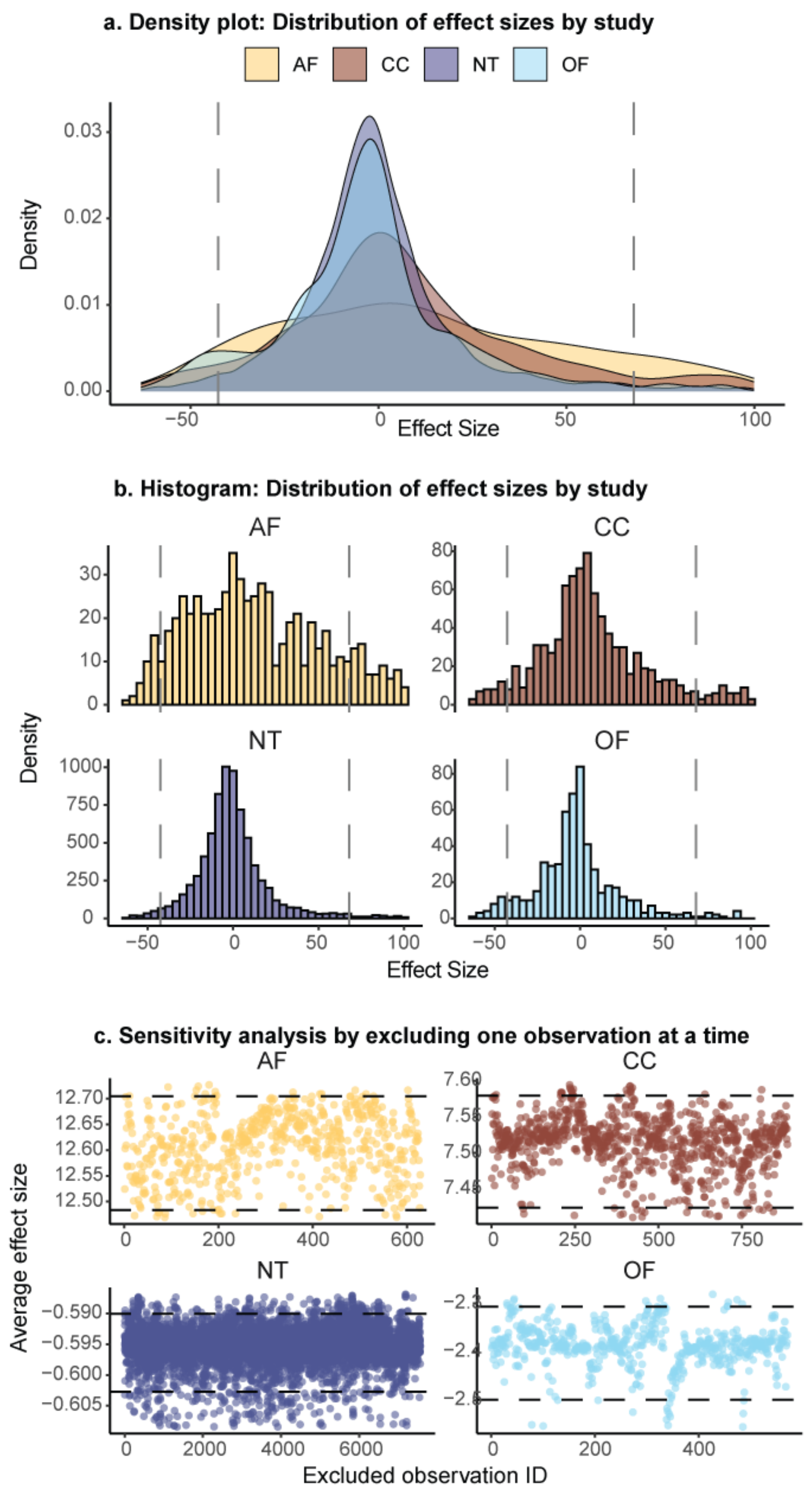

Figure 6: The (a) density plot (b) the sensitivity analysis for each regenerative farming practice. The lower and higher 95% confidence intervals are provided as dashed red lines. AF: Agroforestry, CC: cover crop, NT: no-tillage, OF: organic farming.

3.7. 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 hectares[107] 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.

Another limitation concerns the environmental data used in this analysis. Soil, climate, and topographic variables were obtained from global geospatial datasets rather than measured directly in the field. Although these datasets offer standardized global coverage, they introduce uncertainty due to coordinate inaccuracies and spatial mismatches between coarse rasters and plot-level observations[108,109]. Many meta-analyses report site locations only as approximate centroids, creating potential positional errors when linking field data to environmental covariates[110]. Differences in spatial resolution (e.g. SoilGrids (250 m) and CHELSA (1 km)) can also generate modifiable areal unit problems (MAUP), where averaged values fail to capture local variability[111]. Soil properties such as SOC, pH, and bulk density vary substantially within fields, and modeled data cannot fully reflect this fine-scale heterogeneity[112]. Likewise, interpolated climate and DEM-based terrain attributes may obscure microclimatic differences that strongly influence yields[113]. These uncertainties may affect the precision of detected environmental relationships. Future studies could reduce them by testing sensitivity to extraction scale or by integrating global rasters with field-measured variables where possible.

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. The attribution of yield effects to individual RFPs is further complicated by the frequent bundling of multiple practices within the same study, especially in NT systems. For instance, AF can include alley cropping, forest farming, silvopastoralism, or riparian forest buffers[114-116], while CC species differ in their root structure with fibrous species such as ryegrass or oats controlling erosion more effectively than thick-rooted types like white mustard or fodder radish[117]. Such management diversity can obscure the individual contribution of each practice, highlighting the need for more detailed reporting and standardized classification in future analyses.

This study did not assess how different RFPs contribute to the resilience of farming systems in the face of increasingly frequent climate extremes, such as droughts and floods, which represents 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 failure[118]. 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 along with 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. 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.

Declarations

Funding

This study was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 819202), the Research Council of Finland's Flagship Programme under project Digital Waters (grant no. 359248), Strategic Research Council (SRC) through project 'Water & Food' (grant no. 365512), and Maa- ja vesitekniikan tuki ry.

Competing of Interests

The authors declare no competing interests.

Ethics approval

This study did not involve human participants, their data, or biological material. Therefore, ethical approval and informed consent were not required.

Consent to participate

This study did not involve human participants, and therefore, informed consent was not required.

Data Availability

Topography data were obtained from https://www.earthenv.org/topography . The geomorphological landform grid data was obtained from https://gisstar.gsi.go.jp/terrain2021/. The global stock of soil Olsen phosphorus was accessed via the following platform. Data related to soil properties were downloaded from https://soilgrids.org/. The aridity data were sourced from the platform provided by The global aridity index was obtained from https://www.global-ai-pet.org/global-aridity-index-pet-database. The data generated in this study will be openly available upon publication on the Zenodo platform.

Code Availability

All data analyses were conducted in R (version 4.2.2). The scripts used in this study will be openly available upon publication on the Github/Zenodo platform.

Contributions

K.O.L.H conceptualized and designed the study. K.O.L.H developed the algorithms to define the suitability areas of the regenerative farming practices. K.O.L.H, JP and E.D.D performed the analyses with the support from M.J and M.K. K.O.L.H led the writing of the paper, interpreted the results, created illustrations and revised the paper with support and comments from JP, E.D.D., M.J., J.P., Z.M., and M.K.

References

1 UNCCD. Summary for Decision Makers (Global Land Outlook) 2nd edn. (2022).

2 IPBES, W. Intergovernmental science-policy platform on biodiversity and ecosystem services. *Summary for policy makers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES Secretariat, Bonn, Germany* (2019).

3 Smith, P. *et al.* Status of the World's Soils. *Annual review of environment and resources* **49**, 73–104 (2024).

4 Bodirsky, B. L. *et al.* Global food demand scenarios for the 21 st century. *PloS one* **10**, e0139201 (2015).

5 Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K. & Johns, C. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. *Frontiers in Sustainable Food Systems* **4**, 577723 (2020).

6 Rehberger, E., West, P. C., Spillane, C. & McKeown, P. C. What climate and environmental benefits of regenerative agriculture practices? an evidence review. *Environmental Research Communications* **5**, 052001 (2023).

7 O'Donoghue, T., Minasny, B. & McBratney, A. Digital Regenerative Agriculture. *npj Sustainable Agriculture* **2**, 5 (2024).

8 Schreefel, L., Schulte, R. P., De Boer, I., Schrijver, A. P. & Van Zanten, H. Regenerative agriculture–the soil is the base. *Global Food Security* **26**, 100404 (2020).

9 Khangura, R., Ferris, D., Wagg, C. & Bowyer, J. Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability* **15**, 2338 (2023).

10 Haddaway, N. R. *et al.* How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence* **6**, 1–48 (2017).

11 Ren, X., Zou, W., Jiao, J., Stewart, R. & Jian, J. Soil properties affect crop yield changes under conservation agriculture: A systematic analysis. *European Journal of Soil Science* **74**, e13413 (2023).

12 Su, Y., Gabrielle, B. & Makowski, D. The impact of climate change on the productivity of conservation agriculture. *Nature Climate Change* **11**, 628–633 (2021).

13 Giller, K. E., Hijbeek, R., Andersson, J. A. & Sumberg, J. Regenerative agriculture: an agronomic perspective. *Outlook on agriculture* **50**, 13–25 (2021).

14 Ranganathan, J., Waite, R., Searchinger, T. & Zionts, J. Regenerative agriculture: Good for soil health, but limited potential to mitigate climate change. *World Resources Institute: Washington, DC, USA* (2020).

15 Pittelkow, C. M. *et al.* Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365–368 (2015).

16 Huang, Y. *et al.* Greenhouse gas emissions and crop yield in no-tillage systems: A meta-analysis. *Agriculture, Ecosystems & Environment* **268**, 144–153 (2018).

17 Al-Kaisi, M. M. & Lal, R. Aligning science and policy of regenerative agriculture. *Soil Science Society of America Journal* **84**, 1808–1820 (2020).

18 Knapp, S. & van der Heijden, M. G. A global meta-analysis of yield stability in organic and conservation agriculture. *Nature communications* **9**, 3632 (2018).

19 Baier, C., Gross, A., Thevs, N. & Glaser, B. Effects of agroforestry on grain yield of maize (Zea mays L.)—A global meta-analysis. *Frontiers in Sustainable Food Systems* **7**, 1167686 (2023).

20 Ivezić, V., Yu, Y. & Werf, W. v. d. Crop yields in European agroforestry systems: a meta-analysis. *Frontiers in Sustainable Food Systems* **5**, 606631 (2021).

21 Peng, Y., Wang, L., Jacinthe, P.-A. & Ren, W. Global synthesis of cover crop impacts on main crop yield. *Field Crops Research* **310**, 109343 (2024).

22 Clark, A. J., Decker, A. M., Meisinger, J. J. & McIntosh, M. S. Kill date of vetch, rye, and a vetch—rye mixture: II. Soil moisture and corn yield. *Agronomy Journal* **89**, 434–441 (1997).

23 Thorup-Kristensen, K., Magid, J. & Jensen, L. S. Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy* **79**, 227–302 (2003).

24 Nielsen, D. C. *et al.* Cover crop effect on subsequent wheat yield in the central Great Plains. *Agronomy Journal* **108**, 243–256 (2016).

25 Lal, R. Regenerative agriculture for food and climate. *Journal of soil and water conservation* **75**, 123A–124A (2020).

26 Mattila, T. J. & Häkkinen, L. Exploring the effects of soil structure, nutrients, and farm management on crop root biomass and depth distribution. *Field Crops Research* **327**, 109909 (2025).

27 Oliveira, E. M. *et al.* Effects of conventional, organic and conservation agriculture on soil physical properties, root growth and microbial habitats in a long-term field experiment. *Geoderma* **447**, 116927 (2024).

28 Strock, C. F., Rangarajan, H., Black, C. K., Schäfer, E. D. & Lynch, J. P. Theoretical evidence that root penetration ability interacts with soil compaction regimes to affect nitrate capture. *Annals of botany* **129**, 315–330 (2022).

29 Oldfield, E. E., Bradford, M. A. & Wood, S. A. Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil* **5**, 15–32 (2019).

30 Zhao, C. *et al.* Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of sciences* **114**, 9326–9331 (2017).

31 Myers, S. S. *et al.* Climate change and global food systems: potential impacts on food security and undernutrition. *Annual review of public health* **38**, 259–277 (2017).

32 Zhao, J., Wang, Z., Dong, Y., Yang, Z. & Govers, G. How soil erosion and runoff are related to land use, topography and annual precipitation: Insights from a meta-analysis of erosion plots in China. *Science of the Total Environment* **802**, 149665 (2022).

33 Sun, C., Hou, H. & Chen, W. Effects of vegetation cover and slope on soil erosion in the Eastern Chinese Loess Plateau under different rainfall regimes. *PeerJ* **9**, e11226 (2021).

34 Ewunetu, T., Selassie, Y. G., Molla, E., Admase, H. & Gezahegn, A. Soil properties under different land uses and slope gradients: Implications for sustainable land management in the Tach Karnuary watershed, Northwestern Ethiopia. *Frontiers in Environmental Science* **13**, 1518068 (2025).

35 Pittelkow, C. M. *et al.* When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156–168 (2015).

36 Félix, G. F., Scholberg, J. M., Clermont-Dauphin, C., Cournac, L. & Tittonell, P. Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa. A meta-analysis. *Agronomy for Sustainable Development* **38**, 57 (2018).

37 de la Cruz, V. Y. V., Cheng, W. & Tawaraya, K. Yield gap between organic and conventional farming systems across climate types and sub-types: A meta-analysis. *Agricultural Systems* **211**, 103732 (2023).
38 Karger, D. N. *et al.* Climatologies at high resolution for the earth's land surface areas. *Scientific Data* **4**, 1–20 (2017).
39 Funk, C. *et al.* The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data* **2**, 1–21 (2015).
40 Ahvo, A. *et al.* Agricultural input shocks affect crop yields more in the high-yielding areas of the world. *Nature Food* **4**, 1037–1046 (2023).
41 Poggio, L. *et al.* SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil* **7**, 217–240 (2021).
42 Dash, P. K. in *Remote Sensing of Soils* 357–370 (Elsevier, 2024).
43 Vance, T. C., Huang, T. & Butler, K. A. Big data in Earth science: Emerging practice and promise. *Science* **383**, eadh9607 (2024).
44 Kganyago, M., Adjorlolo, C., Mhangara, P. & Tsoeleng, L. Optical remote sensing of crop biophysical and biochemical parameters: An overview of advances in sensor technologies and machine learning algorithms for precision agriculture. *Computers and Electronics in Agriculture* **218**, 108730 (2024).
45 Xia, L., Lam, S. K., Yan, X. & Chen, D. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? *Environmental Science & Technology* **51**, 7450–7457 (2017).
46 Verret, V. *et al.* Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. *Field Crops Research* **204**, 158–168 (2017).
47 Ding, W. *et al.* Improving yield and nitrogen use efficiency through alternative fertilization options for rice in China: A meta-analysis. *Field Crops Research* **227**, 11–18 (2018).
48 Jian, J., Du, X. & Stewart, R. D. A database for global soil health assessment. *Scientific Data* **7**, 16 (2020).
49 Seufert, V., Ramankutty, N. & Mayerhofer, T. What is this thing called organic?–How organic farming is codified in regulations. *Food Policy* **68**, 10–20 (2017).
50 Kuradusenge, M. *et al.* Crop yield prediction using machine learning models: Case of Irish potato and maize. *Agriculture* **13**, 225 (2023).
51 Wang, Q., Huang, K., Liu, H. & Yu, Y. Factors affecting crop production water footprint: A review and meta-analysis. *Sustainable Production and Consumption* **36**, 207–216 (2023).
52 Grigorieva, E., Livenets, A. & Stelmakh, E. Adaptation of agriculture to climate change: A scoping review. *Climate* **11**, 202 (2023).
53 Baker, N. T. & Capel, P. D. Environmental factors that influence the location of crop agriculture in the conterminous United States. Report No. 2328-0328, (US Geological Survey, 2011).
54 Zomer, R. J., Xu, J. & Trabucco, A. Version 3 of the global aridity index and potential evapotranspiration database. *Scientific Data* **9**, 409 (2022).
55 Leuthold, S. J., Wendroth, O., Salmerón, M. & Poffenbarger, H. Weather-dependent relationships between topographic variables and yield of maize and soybean. *Field Crops Research* **276**, 108368 (2022).
56 Kumhálová, J., Kumhála, F., Matějková, Š. & Kroulík, M. The relationship between topography and yield in different weather conditions. *Precision Agriculture*, 606–616 (2011).
57 Leuthold, S. J., Salmeron, M., Wendroth, O. & Poffenbarger, H. Cover crops decrease maize yield variability in sloping landscapes through increased water during reproductive stages. *Field Crops Research* **265**, 108111 (2021).

58 Martinez-Feria, R. A. & Basso, B. Unstable crop yields reveal opportunities for site-specific adaptations to climate variability. *Scientific Reports* **10**, 2885 (2020).
59 Basso, B., Shuai, G., Zhang, J. & Robertson, G. P. Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Scientific Reports* **9**, 5774 (2019).
60 Amatulli, G. *et al.* A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Scientific data* **5**, 1–15 (2018).
61 Iwahashi, J. & Yamazaki, D. Global polygons for terrain classification divided into uniform slopes and basins. *Progress in Earth and Planetary Science* **9**, 33 (2022).
62 Sainju, U. M. & Alasinrin, S. Y. Changes in soil chemical properties and crop yields with long-term cropping system and nitrogen fertilization. *Agrosystems, Geosciences & Environment* **3**, e20019 (2020).
63 Sainju, U. M., Liptzin, D. & Jabro, J. D. Relating soil physical properties to other soil properties and crop yields. *Scientific Reports* **12**, 22025 (2022).
64 Dewangan, S., Kumari, L., Minj, P., Kumari, J. & Sahu, R. The effects of soil ph on soil health and environmental sustainability: A review. *JETIR, Jun* (2023).
65 Zhang, S. *et al.* Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. *Journal of Environmental Management* **345**, 118531 (2023).
66 McDowell, R., Noble, A., Pletnyakov, P. & Haygarth, P. A Global Database of Soil Plant Available Phosphorus. *Scientific Data* **10**, 125 (2023).
67 Luo, Y., Hui, D. & Zhang, D. Elevated CO2 stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis. *Ecology* **87**, 53–63 (2006).
68 Chen, G. & Weil, R. R. Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research* **117**, 17–27 (2011).
69 Sims, J. T. Soil test phosphorus: Olsen P. *Methods of phosphorus analysis for soils, sediments, residuals, and waters* **20** (2000).
70 Clara, L., Fatma, R., Viridiana, A. & Liesl, W. Soil organic carbon: the hidden potential. *Rome: Food and Agriculture Organization of the United Nations* (2017).
71 Soil Survey Staff, S. A basic system of soil classification for making and interpreting soil surveys. *Agric. Handb.* **436**, 96–105 (1999).
72 Jahn, R., Blume, H.-P., Asio, V., Spaargaren, O. & Schad, P. *Guidelines for soil description*. (Fao, 2006).
73 Croitoru, A.-E., Man, T. C., Vâtcă, S. D., Kobulniczky, B. & Stoian, V. Refining the spatial scale for maize crop agro-climatological suitability conditions in a region with complex topography towards a smart and sustainable agriculture. Case study: Central Romania (Cluj County). *Sustainability* **12**, 2783 (2020).
74 Parthasarathi, T., Velu, G. & Jeyakumar, P. Impact of crop heat units on growth and developmental physiology of future crop production: A review. *Research & Reviews: A Journal of Crop Science and Technology* **2**, 1–11 (2013).
75 Joshi, D. R. *et al.* A global meta-analysis of cover crop response on soil carbon storage within a corn production system. *Agronomy journal* **115**, 1543–1556 (2023).
76 Tanadini, M. & Mehrabi, Z. Does no-till agriculture limit crop yields? *BioRxiv*, 179358 (2017).
77 Egger, M., Smith, G. D., Schneider, M. & Minder, C. Bias in meta-analysis detected by a simple, graphical test. *bmj* **315**, 629–634 (1997).
78 Chandler, J., Cumpston, M., Li, T., Page, M. J. & Welch, V. Cochrane handbook for systematic reviews of interventions. *Hoboken: Wiley* **4**, 14651858 (2019).
79 Basche, A. & DeLonge, M. The impact of continuous living cover on soil hydrologic properties: A meta-analysis. *Soil Science Society of America Journal* **81**, 1179–1190 (2017).

80 Philibert, A., Loyce, C. & Makowski, D. Assessment of the quality of meta-analysis in agronomy. *Agriculture, Ecosystems & Environment* **148**, 72–82 (2012).

81 Tully, K. & Ryals, R. Nutrient cycling in agroecosystems: Balancing food and environmental objectives. *Agroecology and Sustainable Food Systems* **41**, 761–798 (2017).

82 Abdalla, M. *et al.* A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global change biology* **25**, 2530–2543 (2019).

83 Mwangi, O., Mucheru-Muna, M., Kinyua, M., Bolo, P. & Kihara, J. Organic farming practices increase weed density and diversity over conventional practices: A meta-analysis. *Heliyon* **10** (2024).

84 Ponisio, L. C. *et al.* Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences* **282**, 20141396 (2015).

85 Teasdale, J. R. & Mohler, C. L. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science* **48**, 385–392 (2000).

86 Kuyah, S. *et al.* Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agronomy for Sustainable Development* **39**, 1–18 (2019).

87 IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press,, 2021).

88 Allam, M. *et al.* A meta-analysis approach to estimate the effect of cover crops on the grain yield of succeeding cereal crops within European cropping systems. *Agriculture* **13**, 1714 (2023).

89 Blanco-Canqui, H. & Ruis, S. J. Cover crop impacts on soil physical properties: A review. *Soil Science Society of America Journal* **84**, 1527–1576 (2020).

90 Krishnamurthy, L., Krishnamurthy, P. K., Rajagopal, I. & Peralta Solares, A. Can agroforestry systems thrive in the drylands? Characteristics of successful agroforestry systems in the arid and semi-arid regions of Latin America. *Agroforestry Systems* **93**, 503–513 (2019).

91 Khan, M. T., Aleinikovienė, J. & Butkevičienė, L.-M. Innovative organic fertilizers and cover crops: Perspectives for sustainable agriculture in the Era of climate change and organic agriculture. *Agronomy* **14**, 2871 (2024).

92 Phillips, I. *et al.* Combination of inorganic nitrogen and organic soil amendment improves nitrogen use efficiency while reducing nitrogen runoff. *Nitrogen* **3**, 4 (2022).

93 Lori, M., Symnaczik, S., Mäder, P., De Deyn, G. & Gattinger, A. Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PloS one* **12**, e0180442 (2017).

94 Sun, J. *et al.* Regionally adapted conservation tillage reduces the risk of crop yield losses: A global meta-analysis. *Soil and Tillage Research* **244**, 106265 (2024).

95 Vendig, I. *et al.* Quantifying direct yield benefits of soil carbon increases from cover cropping. *Nature Sustainability* **6**, 1125–1134 (2023).

96 Blanco-Canqui, H. & Lal, R. Crop residue removal impacts on soil productivity and environmental quality. *Critical reviews in plant science* **28**, 139–163 (2009).

97 Solangi, F. *et al.* Responses of soil enzymatic activities and microbial biomass phosphorus to improve nutrient accumulation abilities in leguminous species. *Scientific Reports* **14**, 11139 (2024).

98 Hu, N. *et al.* Increasing phosphorus limitation with tree age in tropical forests. *Plant and Soil*, 1–13 (2025).

99 Clausing, S. & Polle, A. Mycorrhizal phosphorus efficiencies and microbial competition drive root P uptake. *Frontiers in Forests and Global Change* **3**, 54 (2020).

100 Jansa, J., Finlay, R., Wallander, H., Smith, F. A. & Smith, S. E. in *Phosphorus in action: biological processes in soil phosphorus cycling* 137–168 (Springer, 2010).
101 Fahad, S. *et al.* Agroforestry systems for soil health improvement and maintenance. *Sustainability* **14**, 14877 (2022).
102 Ngaba, M. J. Y. *et al.* Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. *Plant and Soil* **496**, 589–607 (2024).
103 Futerman, S. I. *et al.* Assessing field-scale rill erosion mitigation by cover crops in arable land using drone image analysis. *Soil and Tillage Research* **246**, 106341 (2025).
104 Barbosa, E. A., Paula, A. L. d., Santos, É. L. d., Barbosa, F. T. & Giarola, N. F. Use of Agricultural Terraces to Control Water Loss on Slopes Cultivated with Grains Under a No-TillAGE System. *Engenharia Agrícola* **45**, e20240186 (2025).
105 Wang, G. *et al.* Effect of Terracing on Soil Moisture of Slope Farmland in Northeast China's Black Soil Region. *Agriculture* **13**, 1876 (2023).
106 Shackelford, G. E., Kelsey, R. & Dicks, L. V. Effects of cover crops on multiple ecosystem services: Ten meta-analyses of data from arable farmland in California and the Mediterranean. *Land use policy* **88**, 104204 (2019).
107 De Las Salas, G. Agroforestry Systems in Latin America. *Turrialba, AMAZON ECOLOGY AND ADAPTATION* **87**, 97–115 (1979).
108 Rohmer, J., Belbeze, S. & Guyonnet, D. Insights into the prediction uncertainty of machine-learning-based digital soil mapping through a local attribution approach. *Soil* **10**, 679–697 (2024).
109 Groß, J. *et al.* Influence of small-scale spatial variability of soil properties on yield formation of winter wheat. *Plant and Soil* **493**, 79–97 (2023).
110 Kinnee, E. J. *et al.* Geocoding error, spatial uncertainty, and implications for exposure assessment and environmental epidemiology. *International journal of environmental research and public health* **17**, 5845 (2020).
111 Maynard, J. J. *et al.* Accuracy of regional-to-global soil maps for on-farm decision-making: are soil maps "good enough"? *Soil* **9**, 277–300 (2023).
112 Wu, B. *et al.* Challenges and opportunities in remote sensing-based crop monitoring: A review. *National Science Review* **10**, nwac290 (2023).
113 Dritsas, E. & Trigka, M. Remote sensing and geospatial analysis in the big data era: A survey. *Remote Sensing* **17**, 550 (2025).
114 Feliciano, D., Ledo, A., Hillier, J. & Nayak, D. R. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems & Environment* **254**, 117–129 (2018).
115 Nair, P. R. *et al.* Global distribution of agroforestry systems. *An introduction to agroforestry: four decades of scientific developments*, 45–58 (2021).
116 Sprenkle-Hyppolite, S., Griscom, B., Griffey, V., Munshi, E. & Chapman, M. Maximizing tree carbon in croplands and grazing lands while sustaining yields. *Carbon Balance and Management* **19**, 23 (2024).
117 Sharma, P. *et al.* The role of cover crops towards sustainable soil health and agriculture—A review paper. *American Journal of Plant Sciences* **9**, 1935–1951 (2018).
118 Raheem, A. *et al.* Physical Management Strategies for Enhancing Soil Resilience to Climate Change: Insights From Africa. *European Journal of Soil Science* **76**, e70030 (2025).

Supplementary Table 1: Crop groups

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

Supplementary Table 2: 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 3: 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