# 4.2. Crop yield change across specific crops and growing degree days

# Across all regenerative and soil conservation practices (RFPs), yield responses varied substantially among crop types (Fig. 2). Considering all RFPs together, cash crops increased by 5.3% (3.2–7.7%), while maize increased by 0.6% (–0.8 to 2.4%). These findings indicate that maize and cash crops benefited most from RFP adoption, although the magnitude of response differed among crop groups. Such variation likely reflects crop-specific physiological traits, management intensity, and their interactions with improved soil fertility and microclimatic regulation under RFPs【19,87】. Maize, with high nutrient and water demand, tends to respond more favorably to improvements in soil organic matter and water retention often achieved through practices such as agroforestry (AF), cover cropping (CC), and organic fertilization (OF).

# Across individual RFPs (Fig. 3), most crops showed positive mean yield gains under CC, while responses were mixed for other practices. Significant increases were observed mainly for maize under AF, CC, and OF, and for cash crops under CC and no-till (NT). This suggests that RFPs emphasizing continuous soil cover and organic inputs are more effective in enhancing yields compared to disturbance-reducing practices alone. The higher yield responses of maize under AF and CC likely result from improved rooting depth, nutrient cycling, and water availability, while the consistent response of cash crops under CC and NT may reflect their adaptability to soil structure improvement and moisture conservation【88,89】.

# Yield responses along growing degree day (GDD, °C y⁻¹) gradients revealed clear temperature-dependent patterns. Across all RFPs, 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. The positive yield responses under higher GDD regimes (> 4000°C y⁻¹) for maize, soybean, and wheat indicate that RFPs are particularly beneficial under warm conditions, likely due to improved soil water retention, microclimate buffering, and enhanced soil organic matter dynamics that sustain productivity under heat stress【88,89】.

# When analyzed by RFP across GDD classes, high-temperature regimes (> 4000°C y⁻¹) resulted in greater 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, whereas wheat showed significant yield increases under CC and OF at 800–2700°C y⁻¹, with positive trends persisting above 6000°C y⁻¹, mainly for CC. These patterns indicate that AF and CC perform best in warmer, high-GDD environments where soil water retention and organic matter cycling mitigate heat and drought stress, while OF provides advantages in cooler or short-season environments due to gradual nutrient release and improved soil structure【90–92】.

# Overall, the results demonstrate strong crop- and climate-dependent yield responses to RFPs. Systems combining organic inputs and soil cover management (CC, AF, OF) generally enhance yields across a wide thermal range, while NT shows more variable outcomes. These patterns highlight the importance of matching management strategies with local thermal regimes to optimize productivity and resilience.

# Results and Discussion

**Results and Discussion**

Across our global dataset, regenerative farming practices (RFPs) produced a modest but statistically significant overall increase in crop yield of ~0.8% (95% confidence interval: 0.3–1.3%) relative to conventional controls. While small in magnitude, this average gain suggests that sustainable intensification is achievable through RFPs. However, yield responses spanned a wide range—including increases, decreases, and neutral outcomes—depending on the specific practice, crop type, and environmental context of each comparison.

Among the practices evaluated, agroforestry (AF) and cover cropping (CC) showed the most consistent positive impacts on yield. In our analysis, AF increased yields by **~12.3%** (95% CI: 9.3–15.5%) and CC by **~7.5%** (5.4–9.6%), both significant improvements. These findings align with previous research highlighting the benefits of diversified cropping systems, though the magnitude of the effect varies widely across studies11,21,80. For example, Ren *et al.* *11* observed yield increases of ~66% under AF and ~11% under CC, whereas a global meta-analysis by Peng *et al.* *21* reported only a 2.6% average increase for cover crops (rising to ~9% in cases using leguminous cover species)81. Such discrepancies likely reflect differences in baseline soil fertility, climate, and management practices among studies. In contrast, no-tillage (NT) and organic farming (OF) in our dataset were associated with slight mean yield declines. NT showed a significant average change of **–0.7%** (–1.2 to –0.2%), and OF a non-significant **–2.0%** (–3.9 to 0.2%). These modest shortfalls may stem from challenges such as limited nutrient availability, increased weed pressure, or transitional yield lags in certain contexts35,82,83.

**Crop-Specific Responses and Growing Degree Days**

Crop-specific responses to RFPs also varied. On average (pooling all RFPs), **cash crops** (e.g. cotton, sugar beet) showed a significant mean yield increase of ~5.3% (CI: 3.2–7.7%), and **maize** yields increased slightly (~+0.6%, CI: –0.8 to +2.4%). Other crop groups (e.g. other cereals, legumes, vegetables) exhibited mixed responses without a consistent overall gain or loss. These patterns suggest that certain crops may benefit more from RFP adoption due to their physiology and management needs. For instance, maize is a high-input, fast-growing crop that could respond strongly to improvements in soil fertility and water retention under practices like AF, CC, or even OF19,84. Enhancements such as greater soil organic matter, improved nutrient cycling, and moderated microclimate in RFP systems may particularly favor maize and other resource-demanding crops.

Temperature regime (growing degree days, GDD) further modulated crop outcomes. We found that yield gains were generally larger in environments with high heat accumulation. At GDD totals above ~4000 °C·year⁻¹, crops like maize, soybean, and wheat showed notably greater yield improvements under RFPs – especially in AF and CC systems – compared to lower-GDD environments or conventional practices. AF and CC likely confer an advantage in hot climates by conserving soil moisture and reducing heat stress: trees and cover crops provide shade, improve soil structure, and reduce evaporation, thereby buffering crops against drought and extreme heat85,86. By reducing erosion and enhancing water infiltration, these practices help retain both moisture and nutrients, making crops more resilient during dry spells and intense rain events85,86. Conversely, under very low GDD conditions (short or cool growing seasons), organic farming tended to perform comparatively well – indeed, many of the largest yield increases at GDD < 800 °C were observed in OF trials for maize, rice, and soybean. In such cool environments, the gradual nutrient release from organic amendments can better synchronize with slower crop growth, improving nutrient use efficiency87,88. Improved soil structure and moisture retention under organic management also help buffer crops against thermal limitations89, and pest and disease pressures are often lower in cooler climates, reducing the need for synthetic inputs. These findings underscore that crop characteristics and thermal climate context play a crucial role in the performance of regenerative practices.

**Influence of Climate (Aridity and Climate Zones)**

Climate context strongly modulated yield outcomes under RFPs. In our data, RFP adoption was most beneficial in **arid** and **temperate** regions, while **continental** climates saw slight yield declines and **tropical** regions showed essentially no change. For example, mean yield increases in arid climates were on the order of **+3.9%** (CI: 2.6–5.2%) and in temperate climates **+1.8%** (1.0–2.7%), compared to a decline of **–1.7%** (–2.4 to –1.1%) in continental zones and a non-significant **+0.4%** (–1.3 to +2.5%) in the tropics. These broad patterns mirror an underlying moisture gradient: sites in dry environments had the strongest RFP benefits. Using the aridity index (AI), we found average yield gains of ~**9.1%** in arid zones (AI 0.05–0.20) and ~**2.7%** in semi-arid zones (AI 0.20–0.50), whereas sub-humid to humid areas (AI > 0.50) showed neutral or slightly negative responses. Such results indicate that RFPs are particularly advantageous under water-limited conditions, where improved soil structure, higher organic matter, and better water-holding capacity directly translate into enhanced crop productivity and drought resilience.

We also observed that the relative performance of each practice varied with climate. In arid environments, **AF** and **NT** produced the greatest yield advantages, likely because both practices conserve soil moisture, maintain protective cover, and reduce erosion – 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 scarce water, potentially reducing yields90. 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. In humid regions, by comparison, the yield differences between RFPs and conventional practices were smaller. Even so, AF still achieved notable gains in many temperate-zone (high-rainfall) sites, which likely reflects improvements in nutrient cycling, reduced leaching, and enhanced soil structure – functions especially valuable in wetter systems prone to runoff and nutrient loss. Overall, these climatic patterns highlight that the success of RFPs depends strongly on local water balance and weather conditions. Tailoring the choice of regenerative practice to the prevailing climate (e.g. prioritizing moisture-conserving practices in dry areas) can maximize productivity and resilience. Moreover, as climate change is projected to expand arid regions, the drought-mitigating effects of practices like AF and NT could become increasingly important for maintaining yields under drier future conditions15,91,92.

**Influence of Soil Properties**

Soil characteristics were another key determinant of yield variability under RFPs. In general, we found that RFPs delivered the largest yield gains on soils of lower inherent fertility or poorer condition. Significant increases were observed in soils with **low soil organic carbon** (e.g. SOC < ~5–10 g·kg⁻¹), **coarse texture** (sandy soils), and in soils that were **strongly acidic or alkaline** (as opposed to neutral pH). Yield improvements were also pronounced in nutrient-poor conditions – for instance, in soils with low to moderate available phosphorus (P) and those with low to medium bulk density. By contrast, in **neutral-pH** soils and in already fertile environments (e.g. high SOC or high P levels), RFPs often conferred little to no yield benefit, and in some cases yields slightly declined relative to conventional practice. These patterns suggest that regenerative practices are particularly effective at rehabilitating **marginal or degraded soils** by enhancing nutrient cycling, improving soil structure, and increasing biological activity15,93,94. Consistent with this, the greatest average yield improvements in our dataset were seen on inherently poor soil types (e.g. Lixisols, Arenosols, Calcisols), whereas more chemically or physically constrained orders like Alisols and Gleysols showed negligible or negative yield responses under RFPs.

At the same time, we observed diminishing returns for RFPs in high-fertility soils. AF and CC, for example, only produced moderate yield gains under high-SOC conditions, reflecting that when soils are already healthy and well-stocked with organic matter, there is less headroom for improvement. In coarse-textured (sandy) soils, on the other hand, all RFPs except OF showed positive yield effects – with CC and NT in particular achieving statistically significant increases – consistent with evidence that conservation practices improve water retention and soil structure in sandy soils95. We also noted that yield **reductions** under RFPs were most prevalent in **neutral pH** soils and in **P-rich** soils (>21.4 mg·kg⁻¹ P). This may reflect nutrient imbalances or the reduced relative advantage of RFPs in already fertile settings. An interesting exception was observed in agroforestry systems under high-P conditions: despite high background fertility, AF still achieved a substantial yield boost (median ~40% increase) even when soil P exceeded 21 mg·kg⁻¹. This aligns with research showing that while AF improves nutrient cycling, these systems can continue to benefit from phosphorus supplementation in P-limited soils. Phosphorus is often a limiting nutrient in highly weathered tropical soils because it becomes fixed and unavailable to plants; yet adequate P is crucial for plant growth and for processes like biological nitrogen fixation in leguminous trees96,97. Studies have shown that adding P can stimulate microbial activity, mycorrhizal associations, and root development, resulting in greater nutrient uptake and biomass production98,99. Thus, the large yield increases we observed for AF even at high P levels likely reflect the combined effects of improved nutrient acquisition, enhanced soil structure, and biological activity, supporting the idea that targeted P inputs in nutrient-poor soils can further boost the productivity of agroforestry systems.

**Influence of Topography**

Topographic factors also influenced yield outcomes under RFPs. Overall, regenerative practices tended to confer the greatest benefits at higher elevations and on non-flat terrain. We observed significant positive yield responses at **elevations > 250 m** above sea level, and in our full dataset the largest mean gains occurred on **gentle slopes** (~1–5% gradient) and on **strongly sloping land** (15–30% slope). These results suggest that RFPs improve water infiltration and reduce runoff across a range of landscapes, thereby mitigating yield losses due to erosion or poor drainage on sloping terrain. Such topography-related differences are consistent with previous studies showing that slope position and elevation modulate the benefits of conservation agriculture via their effects on soil moisture dynamics, erosion rates, and microclimates100,101.

Examining individual practices, we found that AF was most effective on **level to gently sloping areas** (<15% slope) and also showed strong yield gains in **high-elevation settings** (e.g. mountain slopes, high plateaus). These are contexts where tree-crop systems help stabilize soil and improve drainage, reducing erosion and fostering favorable microclimates for crops102,103. OF likewise performed well on moderate highland slopes, perhaps due to enhanced nutrient cycling in those well-drained soils. CC showed substantial yield improvements on both gentle and steep slopes, thanks to ground cover that curtails erosion and builds soil structure. Meanwhile, in lower-lying landforms such as terraces and valley bottoms, both CC and NT were associated with yield increases – likely because these practices help retain moisture and prevent soil degradation by stabilizing the sediment and organic matter moving downslope. Empirical evidence supports these mechanisms: cover crops have been shown to reduce rill erosion by ~30–60% relative to bare fallow104, and implementing no-till alongside terracing can cut surface runoff by over 90%, increasing moisture storage in valley soils and stabilizing yields during droughts105,106. By trapping upslope sediments and organic matter, CC and NT also enrich depositional areas (like valley bottoms) with additional nutrients, which helps sustain fertility and crop productivity there.

**No-Tillage Management Strategies**

Our subgroup analysis of no-tillage practices confirmed that NT’s yield impact is highly contingent on complementary management and climate. As shown in **Figure 6**, NT produced the strongest yield benefits in **arid** and **temperate** regions **when** combined with key practices such as adequate nitrogen fertilization, continuous soil cover (residues/mulch), effective weed control, and crop rotation. Under these synergistic conditions, NT yields were up to ~40% higher than conventional tillage in arid climates and ~20% higher in temperate climates. Such combinations likely enhance soil water retention and nutrient availability while minimizing evaporative losses – factors critical for productivity in water-limited environments. These results align with earlier meta-analyses showing that NT performs best under dry conditions when integrated with residue retention and sound nutrient management15,107,108. By contrast, in cooler **continental** climates, NT showed mostly neutral to slightly negative effects on yield across the management regimes we analyzed. Even adding rotations and weed control did not reliably produce yield gains in continental settings, possibly due to shorter growing seasons or limited residue persistence in those colder environments. (Inclusion of weed control and crop rotation did appear to partially mitigate yield penalties, but the overall effect of NT in continental zones remained small or non-significant.)

In **tropical** regions, our analysis found that NT generally led to yield **reductions** under most management combinations. Even with supplemental nitrogen and weed control, or with rotations, no-till tended to underperform conventional tillage in the tropics. These negative outcomes likely stem from several interacting constraints. Highly weathered tropical soils often have low structural stability and can become compacted when not periodically tilled15,109, which limits root growth and water infiltration. Warm, humid conditions also accelerate residue decomposition and can foster pest and disease outbreaks, reducing the protective mulch benefits of no-till110,107,111. In addition, many tropical soils are inherently acidic and nutrient-poor; without tillage to incorporate organic matter, and with insufficient residue cover in many cases, nutrient cycling and microbial activity may remain too low to sustain yields65. Collectively, these factors diminish NT performance in humid tropical environments, even when standard management augmentations are in place.

Nevertheless, targeted management can mitigate many of NT’s constraints. Integrating no-till with cover cropping, mulching, or organic amendments can improve soil structure and biological activity, while rotations with deep-rooted species help alleviate compaction and tap nutrients from deeper layers112,113,114. Over the longer term, sustained NT adoption may also build soil organic carbon and improve aggregate stability, gradually offsetting initial yield declines115. Overall, our findings underscore that NT is not universally beneficial or detrimental – rather, its effectiveness depends on pairing no-till with supportive practices and applying it in agroecological settings where it is most likely to succeed.

**Publication Bias and Result Robustness**

We assessed our meta-analysis for publication bias and the influence of individual studies on the results (Figure 7). The distribution of effect sizes was approximately normal and showed no strong asymmetry, suggesting an absence of systematic publication bias in the dataset. Jackknife sensitivity tests (iteratively removing one study at a time) likewise indicated that no single study unduly influenced the overall outcome: the pooled mean effect size remained essentially unchanged (within the original 95% CI) regardless of which study was omitted. Although a few individual studies had relatively larger effects (their exclusion caused minor shifts in the estimate), their impact on the aggregate result was negligible given the large sample size. This attenuation of single-study influence supports the robustness of our findings, consistent with observations from other large-scale meta-analyses116. We therefore retained these influential studies, as excluding them would not meaningfully alter the conclusions.

**Limitations and Future Directions**

Despite the broad scope of this analysis, several limitations should be noted. **First**, the data coverage was uneven across regions and practices, which may affect the generalizability of the results to underrepresented contexts. For example, no-tillage studies comprised a large portion of our dataset, whereas far fewer observations were available for AF, CC, or OF. Geographically, the studies were heavily skewed toward Europe and North America for NT and OF, and we had no AF studies from Latin America despite that region hosting hundreds of millions of hectares under agroforestry systems117. These imbalances mean that our pooled results – and even some subgroup findings – are driven disproportionately by conditions that have been well-studied. More globally representative data, especially more studies on AF, CC, and OF in tropical and developing regions, are needed to confirm whether the patterns observed here hold universally.

**Second**, our analysis relied on global geospatial datasets for climate, soil, and topography variables rather than site-specific field measurements. While this approach provided standardized environmental information for all study sites, it inevitably introduced some uncertainty due to potential coordinate errors and scale mismatches between coarse global grids and actual field conditions118,119. Many meta-analyses only report approximate site locations (e.g. the centroid of a region), which can cause small positional errors when linking to climate or soil data120. Moreover, the spatial resolution of datasets like SoilGrids (~250 m) or CHELSA climate (~1 km) is much coarser than plot-level heterogeneity, leading to a modifiable areal unit problem (MAUP)121. The extracted soil values (e.g. SOC, pH, bulk density) may not fully capture fine-scale variability – these properties can vary greatly even within a single field122. Likewise, interpolated climate and terrain data might mask local microclimates or landscape features that strongly affect yields123. Such uncertainties could blur some of the environment–yield relationships identified. Future studies could address this by testing the sensitivity of results to different spatial averaging scales or by incorporating actual field-measured soil and climate data where available.

**Third**, our study focused exclusively on **yield** as the outcome, even though RFPs are often promoted for their broader agroecosystem benefits (improving soil carbon, biodiversity, climate resilience, etc.). This narrow focus may miss important trade-offs and co-benefits that influence adoption decisions by farmers and policymakers. Moreover, attributing effects to individual practices is complicated by the fact that many studies bundle multiple practices or different implementations. For instance, “agroforestry” encompasses diverse systems (from alley cropping and forest farming to silvopastoral and riparian buffer systems124–126), and the impacts of cover crops can vary by species (e.g. fibrous-rooted ryegrass vs. tap-rooted radish have different effects on erosion control127). Such heterogeneity means that what we categorized as one practice can include a range of configurations, potentially obscuring specific contributions of each element. Future meta-analyses would benefit from more detailed reporting on management combinations and from evaluating outcomes beyond yield (such as soil health indicators or economic returns) to provide a more holistic assessment of RFP performance.

**Finally**, we did not explicitly examine how RFPs influence **yield stability** under extreme weather events. Resilience to climate extremes (droughts, floods, heatwaves) is a critical aspect of sustainable agriculture and could reveal additional advantages of these practices. There is evidence that improvements in soil structure and water-holding capacity under RFPs can buffer crops against extreme droughts, potentially preventing total crop failure in bad years128. In practice, a modest but stable harvest achieved via enhanced soil health and water management may be preferable to a higher peak yield that collapses under stress. We suggest that future research prioritize analyses of yield variability and long-term resilience: understanding how RFPs affect yield stability, soil health, and ecosystem services under increasingly frequent climate extremes will be key to gauging their true value for sustainable food production and farmer livelihoods.

**Figure 2:** Distribution of the percentage change in yield (effect size) across regenerative farming practices, crop groups, soil properties, topography, and climatic variables. Points show mean differences (%), and error bars indicate 95% confidence intervals. Categories whose 95% CI does not cross 0 (vertical red line) differ significantly from the conventional control.

**Figure 3:** Distribution of effect sizes across crop groups and climate variables for different regenerative farming practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 (vertical red line) are significantly different from controls. *V\_F\_others* = Vegetables, fruits and other crops; GDD (×1000) = growing degree days.

**Figure 4:** Distribution of effect sizes across soil properties for different regenerative farming practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 differ significantly from controls. *P* = phosphorus, *SOC* = soil organic carbon, *BD* = bulk density.

**Figure 5:** Distribution of effect sizes across topographic variables for different regenerative farming practices. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 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; *Lw\_plain* = low plain (sinks <50%).

**Figure 6:** Distribution of effect sizes (%) across different no-tillage (NT) management regimes (combinations of practices). *N* = nitrogen fertilization; values in parentheses are the number of observations for each regime. Points show means; error bars are 95% CIs. Categories whose 95% CIs exclude 0 differ significantly from controls.

**Figure 7:** (a) Density plot of effect sizes and (b) jackknife sensitivity analysis for each regenerative practice. The lower and upper 95% confidence bounds are shown as dashed red lines. *AF* = agroforestry, *CC* = cover cropping, *NT* = no-tillage, *OF* = organic farming.

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