**Introduction**

More than 70% of the Earth’s land—once covered by forests and natural ecosystems—has now been transformed for human use, with agriculture alone occupying roughly 40% of global land area. This expansion of farming and grazing has come at a steep environmental cost: one-third of the world’s soils are already degraded and fertile topsoil is being lost at an estimated **24 billion tons per year**. Food production is also a major contributor to climate change, accounting for about **34% of global greenhouse gas emissions**. Meanwhile, to feed a growing and more affluent population, global food demand is projected to rise substantially in coming decades. In this context, there is an urgent emphasis on sustainable agricultural pathways that restore land, protect biodiversity, and mitigate greenhouse gases.

Regenerative agriculture has emerged as a promising alternative farming strategy aimed at meeting future food needs **while reducing external inputs, improving soil health, and minimizing environmental damage**. Although there is no universal definition of “regenerative” agriculture, most concepts center on rebuilding soil quality as a foundation for sustainable production. In practice, regenerative farming involves implementing various **soil conservation practices (SCPs)** – such as reduced or no tillage, planting of cover crops, integration of perennials or agroforestry, and organic soil amendments – to enhance ecosystem functions. Studies have documented numerous environmental benefits from these practices, including increased soil organic carbon, better soil structure and water infiltration, and lower net greenhouse emissions. **However, the impacts of regenerative techniques on crop yields are less clear and often debated.** While some farmers and researchers report yield gains under practices like no-till and cover cropping, others have observed neutral or even reduced yields in certain contexts. This variability in outcomes suggests that the benefits of soil-conserving practices for productivity may depend on specific crops and environmental conditions.

**Yield outcomes under different SCPs have indeed shown mixed results.** On one hand, various long-term trials and meta-analyses indicate that adopting conservation practices can maintain or even increase crop yields. For example, the technique of no-till (NT) farming often performs well in water-limited environments: a global analysis found that NT, especially when combined with crop rotation and residue retention, significantly **boosted rainfed crop yields in dry climates**, and during a drought period one study reported **~60% higher maize yields** under no-till compared to conventional plowing. Another meta-analysis observed that no-till increased barley yields by nearly 50% in semi-arid regions. On the other hand, in humid or tropical settings (for instance, continuous maize systems in the tropics), no-till has sometimes led to **yield declines**, particularly if not accompanied by other supportive practices. One comprehensive study found that introducing crop rotation and leaving residues with no-till achieved similar yield stability to conventional tillage, but that strictly **organic farming systems yielded about 15% lower** on average than their conventional counterparts.

A similar pattern of context-dependent results is seen with other regenerative practices like **agroforestry (AF) and cover cropping**. In tropical and subtropical regions, incorporating trees on farms (agroforestry) tends to benefit crops – a global review reported **7–16% higher crop yields** on average in agroforestry systems under those climates. In temperate zones, however, the effect can be the opposite: European agroforestry experiments have shown that as trees mature, **crop yields can decline by ~2–3% per year** due to competition for light and resources. Cover crops (non-harvested crops grown to cover and enrich the soil) likewise exhibit trade-offs. Studies have found that using cover crops, especially **nitrogen-fixing legume covers on coarse, nutrient-poor soils, can increase subsequent crop yields** – in some cases by around 14% or more. Cover cropping can improve soil moisture retention and fertility, which helps yields in certain dry or low-fertility conditions. **In other cases, however, cover crops may slightly reduce yields of the following cash crop**, typically by a few percent, due to competition for water or nitrogen. For instance, a recent meta-analysis of dryland systems concluded that cover crops increased crop yields in wetter tropical climates (by ~15% on average) but led to modest yield penalties in arid and temperate dryland climates (on the order of 10% or less). In situations where regenerative practices do not significantly raise or lower yields in the short term, they often still help **stabilize production over time** – a crucial benefit on degraded lands where conventional yields would likely continue to fall. Overall, the inconsistent yield responses across different studies underscore that multiple interacting factors determine whether a given SCP will boost or hinder crop performance.

**Crop yields are influenced by a complex combination of soil, climate, topographic, and management factors.** For example:

* **Soil properties:** Characteristics like pH, organic carbon content, nutrient levels (e.g. nitrogen, phosphorus), texture, and bulk density directly affect a soil’s water-holding capacity, root growth, and nutrient availability to plants. Healthier soils with ample organic matter can better support high yields by retaining moisture and supplying nutrients.
* **Climate conditions:** 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. Sufficient rainfall or irrigation, and favorable temperatures during the growing season, are critical for realizing potential yields.
* **Topography:** 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. 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.

Integrating data on these environmental factors is crucial for developing **tailored, site-specific farming systems** that optimize both crop productivity and environmental benefits. The variability in outcomes for practices like no-till and cover crops can often be explained by differences in soil type, rainfall patterns, or terrain between study sites. *In other words, the success of a regenerative practice is context-dependent.* To truly understand the yield effects of SCPs, one must account for the underlying soil conditions, climate stressors, and landscape features at each location.

However, **most existing studies of soil conservation practices lack comprehensive data on these key environmental variables.** 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, or cation exchange capacity – nor do they fully capture site characteristics like elevation and slope or climate indices like growing degree-days and seasonal moisture levels. Additionally, previous global comparisons of sustainable farming techniques have usually examined *one practice at a time* (e.g. only no-till vs. conventional, or only chemical vs. organic inputs). Such studies rarely attempt to compare the relative effectiveness of **multiple regenerative practices across different environments and crop types simultaneously**. This piecemeal approach leaves a significant knowledge gap: we still have a limited understanding of *how and why* yield responses to different SCPs vary under diverse soil and climate conditions. There is a clear need for broader analyses that bring together many practices and environmental gradients, to identify where regenerative agriculture is most likely to succeed in boosting yields (or where it might trade off yields for other benefits).

Fortunately, 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 observation” datasets** can provide high-resolution information on climate, topography, and soil properties virtually anywhere on the planet. For example, 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. Climate datasets such as **CHIRPS** (Climate Hazards InfraRed Precipitation with Station data) and reanalysis products like **ERA5-Land** supply detailed rainfall and temperature data over decades. Meanwhile, the **SRTM** digital elevation model (at ~30 m resolution) and similar terrain datasets capture fine-scale variations in elevation and slope. By extracting these variables for the locations of field experiments, researchers can characterize each site’s environmental context without having had to measure everything on the ground. Leveraging such global data enables more robust, large-scale assessments of factors influencing crop yields – essentially allowing us to “scale up” from individual trial results to broader patterns.

In our study, we capitalize on these developments by **combining field trial data with collated global environmental data** to evaluate multiple soil conservation practices side by side. Specifically, we gather results from numerous experiments worldwide that compared regenerative practices (like no-till, cover cropping, agroforestry, organic amendments, etc.) against conventional controls, and for each site we overlay information on climate, soil, and topography drawn from global datasets. This approach allows us to assess how yield responses to different SCPs **vary across a wide range of climatic zones, soil conditions, and landscape positions**. By analyzing many practices and environmental variables together, our study provides a more comprehensive, comparative perspective on regenerative agriculture 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 regenerative agriculture can best contribute to both food security and sustainability.

Of course, the usefulness of global datasets depends on their accuracy and resolution, so it is important to note that these sources have undergone validation. **Peer-reviewed studies have shown that modern global soil and climate datasets can reliably approximate on-the-ground measurements.** For instance, SoilGrids’ estimates of soil organic carbon and texture have been tested against thousands of soil samples worldwide – showing errors typically under 10% for soil organic carbon and a strong correlation (R² > 0.7) between mapped and observed clay percentages in well-studied crop regions (Hengl et al., 2017; Tóth et al., 2018). Similarly, the CHIRPS rainfall product and ERA5-Land temperature reanalysis have demonstrated high fidelity to weather station data, with biases on the order of only **0.5 mm per day for precipitation** and **under 1°C for temperature** in agricultural areas (Funk et al., 2015; Muñoz-Sabater et al., 2021). Digital elevation models like SRTM are fine-grained enough to capture micro-topographic features that influence field conditions – for example, small elevation differences that can drive soil moisture variations and erosion. In fact, terrain attributes from SRTM have been shown to explain up to ~20% of yield variability in certain slope-sensitive cropping systems (e.g. rice terraces and hillside coffee farms) (Zhang et al., 2019). These validations give confidence that **global Earth observation data can meaningfully augment field-level studies**, allowing us to analyze environmental drivers of yield outcomes across large regions.

By extracting consistent soil, climate, and topographic data for each experimental site in our dataset, we are able to directly examine how site conditions modulate the yield impacts of regenerative practices. We then analyze and discuss the emerging patterns – for example, whether no-till tends to work better on certain soil types, or how cover crop benefits might depend on rainfall amounts – in light of the existing literature. This **spatially explicit, data-driven approach** enables us to interpolate between scattered field trials and identify broader trends in where and why regenerative agriculture succeeds. Ultimately, by situating our findings in the context of prior empirical evidence, we provide a richer understanding of how environmental factors influence crop yield responses under different soil conservation practices, and we highlight pathways for tailoring regenerative agriculture to diverse global conditions.