**Evaluating effect size distribution of different regenerative agriculture practices across soil, climatic and topographical factors**

**Environmental factors**

* Climatic / bio climatic variables
* Topographical variables
* Soil properties

Climatic / bioclimatic variables

Topographical variables

Soil

properties

Farmer

management

**Figure:** Factors affecting effect size of the different regenerative agriculture practices

# Introduction

More than 70% of the Earth’s land area which was initially covered by forests and wildlands have been transformed to various use by human being1. A large fraction of such use is devoted to agriculture occupying about 40% of the world land area. However, food production results in a huge environmental footprint with one-third of soils in the world being degraded and fertile soil being lost at the rate of 24 billion tons of topsoil every year2 along with about 34% of global greenhouse gas emissions3. Meanwhile, it is projected that food production would have to increase in the future to satisfy both the need of the global growing population and the increase in per capita demand4. In this context, sustainable pathways that would contribute to land restoration, biodiversity protection and GHG mitigation are more and more emphasized.

Regenerative agriculture (RA) has emerged as an alternative farming strategy seeking to achieve global food security by reducing the use of external inputs, improving soil health and minimize environmental damage5-7. The RA involves different practices (RAP) such as reduced or not tillage (NT), cover crop (CC), perennials and agroforestry (AF), organic farming (OF), intercropping (IN) as well as crop-livestock integration6,8. Previous reviews reported potential beneﬁts of different RAP for increasing soil organic carbon (SOC) and soil water uptake as well as GHG mitigation climate mitigation 6,8,9. However, yield outcomes through the implementation of RAP are subject to many controverses.

Some previous studies showed that RAP could potentially result in increasing yields while others reported a neutral or declining trends10,11 after implementation. While evaluating the outcome of different crops and environmental variables on NT as compared to conventional tillage (CT) yields, Pittelkow, et al. 12 showed that NT impact on yield is dependent upon the region with increasing trend in moisture-limited arid regions while declining patterns are observed in tropical regions with maize-based systems. A global meta-analysis based on740 paired measurements from 90 peer-reviewed articles showed that NT increased barley yield by 49% especially in dry climate13. In a drought period, about 60% higher maize yield was observed under NT management compared to CT14. 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 CT15. The same study showed that OF had 15% lower yield compared to CT.

Under AF management, findings showed that yield either increased by 7 – 16 % in crop yield especially in subtropical and tropical zones16, or reduced by 2.6 % every year in European areas depending on the density and age of the trees17. While about 14% yield increase is reported under CC especially in coarse soil texture and dryland areas along with the use of leguminous cover crops18, about 3% yield reductions observed especially for cash crops in temperate soils19,20. About 10% decrease in wheat yield was observed following cover cropping21. Findings related to the analysis of the benefits and management of IN practices revealed that average grain yields were 22.3% higher in intercropped systems compared to monocultures of the same crops22 while other reported 39% reduction in primary maize yield compared to pure maize yield23. In context whereby there is no significant increase or decrease, some studies reported that yields could be sustained for longtime under RAP especially for degraded soils24.

The discrepancy of yield outcomes under different RAP showed that various factors interplay to determine the magnitude and direction of crop yields for farmers. However, farmers, decision makers and other stakeholders might be interested in having a better understanding on how environmental factors affect crop yield changes under different RAP. Though previous meta-analytic studies have analyzed the variation in productivity between regenerative and CT managements, they mostly focus on a single type of RAP 23,25-28 without investigating their comparative potential across various factors and crop types at a global scale. To our knowledge, these studies do not include or when reported have incomplete records of key soil variables such as bulk density, soil organic carbon, phosphorus, pH, texture, cation exchange capacity, or topographic variables such as elevation and slope or climate variable such as temperature, precipitation, crop growing degree days etc. Consequently, these studies do not involve a large range of environmental factors except for some NT studies which considered alongside management variables soil texture 26,29 or aridity25 as well as climate zones or climatic variables such as temperature and precipitation. However, advances in remote sensing technology in recent decades have resulted in the existence of global earth data with the affordability and accessibility of satellite imagery which provide valuable information on environmental conditions and variables related to soil properties (e.g. soilGrids), climate, topography etc. which in turn are potential factors affecting crop yields30-32. Our current study is unique in that it focuses on different RAP and their influence on relative crop yields across climatic, topographic variables and additional soil properties beyond texture. Therefore, the objective of this paper was to take advantage of global earth and field experiment data to assess the distribution of RAP related relative yields among different conditions defined by environmental factors at a global scale.

* Identify potential optimal pathways for productions across different factors----------
* What is the optimal application conditions for a specific management ?

# Materials and methods

# Data collection

Different global meta-analysis data from Xu et al.26, Jian et al.33, Pittelkow et al.25, Xia et al.34, Verret et al.35, Ding et al.36 and Felix et al.27 were considered in the present study. A preliminary quality check was carried out to remove duplicates studies as well as outliers based on the relative yield (relative yield > 2. 5 t/ha). A total of 10 232 comparisons between RAP and CT were derived from 758 publications covering 773 sites worldwide (Figure 1). After compiling the data, the crop types were classified into seven groups with the most cultivated crops in the world such as maize, wheat, soybean and rice considered separately. The remaining crops were categorized cereal, cash-crop and vegetable & fruits and others (see Table 1 in annex). The compiled data cover the following RAP practices : NT, AF, CC and OF.

A map of the world with black and white text

Description automatically generated

Figure 1: Global distribution of the study sites

# Environmental and management effect size moderators

The impact of the RAP on ES was assessed based on 3 environmental components: climate, soil properties and terrain. For each of the three components, a number of indicators was identiﬁed (Table 1).

Climate, soil properties and terrain variables has been documented to have a major impact on crop growth and food production37-40. 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 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)41. The Growing Degree (GDD) measures the heat accumulation over the growing season 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. 42.

Terrain attributes interact with weather to affect soil temperature and moisture43,44. Water stress occurs most likely in upslope positions with lower and higher variability in yields compared to lower slope positions45-47. Terrain indicators such as terrain and slope (1 km) were obtained via the platform provided by the global study of Amatulli, et al. 48. Additionally, the geomorphological landform grid (250 m) data produced by Iwahashi, et al. 49 was considered.

Soil properties determine the local environment for crop growth by affecting soil aeration, nutrient cycling and root growth50,51. 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 activity52,53. Global soil properties such as soil texture (sand, silt, clay), bulk density (BD), soil organic carbon (SOC), pH were downloaded from the SoilGrids (250 m) platform 54. The global stock of soil Olsen phosphorus came from the global study carried out by McDowell et al.55

In addition, additional management variables such as cover crop (yes/no), N fertilizer (yes/no), weeding (yes/no) and rotation (yes/no) were considered for NT. Consequently, under each component, the distribution of the ES under NT was further analyzed for each of these management variables.

# Data analysis

The data analysis focused on the effect size (ES), i.e. the response ratios (RR) of crop yield to these management systems and was assessed by taking the natural logarithm calculated of RR following Luo, et al. 56 : RR = ln(XT/XC) where XT and XC are the yield value under treatment (NT, AG, CC, or OF) and control, respectively. The ES was expressed as percentage change for better interpretability following Ren, et al. 57: RR (%) = (RR - 1)\*100.

Joshi et al., 2023

To perform this analysis, separate means and their 95% CIs for each of the moderators were determined by assigning each one as a sole co-variate in the original multilevel meta-analytic mixed-effects model described above. The mean cover crop effect for each moderator was considered significant if their 95% CIs did not contain zero (p < 0.05) and the treatment was considered different if the 95% CIs did not overlap. Moderator analysis on cover crop SOC responses was conducted by grouping the metadata into the following categories.

Richner et al., 2014

Bootstrapping was used to calculate 95% conﬁdence intervals by resampling the mean of the response ratio 1000 times. If the conﬁdence interval included zero, the effect size was considered to be non-signiﬁcant. Using a response ratio has the additional advantage of avoiding the effects of plot size variation (Hedges et al., 1999). We calculated the response ratio for several data sets: (i) for the entire data set, (ii) for data sets grouped by crop type (cereal, root crop or undeﬁned) and (iii) for data sets grouped by study design.

Moderator analysis was conducted to determine the RAP effects on percent change of the ES. This analysis was carried out by grouping the metadata into the following categories:

* Crop groups. The previously defined crop groups were considered: maize, wheat, soybean and rice, cereal, cash-crop and vegetable & fruits and others.
* Bulk densities. Low values of BD describe permeable soils allowing plant to reach the nutrient and water easily while high values denote a compacted soil with high mechanical impedance resulting in limited roots growth. It was categorized into three different categories: low (< 1.2 kg/dm3) , moderate (1.2 kg/dm3 < BD < 1.47 kg/dm3), high (BD > 1.47 kg/dm3)58. cite
* pH. Three categories were considered: acidic soils (pH < 6.3,) neutral soils (6.3 < pH < 7.4) and alkaline soils (pH > 7.4). cite
* Phosphorus. The P distribution classes were low: P < 10.9 mg/kg, moderate: 10.9 mg/kg < P < 21.4 mg/kg and High : P > 21.4 mg/kg. cite
* Soil organic carbon. Three categories were considered: SOC < 5 g/kg, 5 g/kg < SOC < 10 g/kg and SOC > 10 g/kg. cite
* Soil texture: These textures were grouped into fine (clay, silty clay loam, clay loam, and sandy clay), medium (silt loam and loam), and coarse (sandy loam and sandy). Cite
* # 1: fine (clay, silty clay loam, clay loam, and sandy clay) : cl SiClLo ClLo SiCl SaCl SaClLo
* # 2: medium (silt loam and loam) Si SiLo Lo
* # 3: coarse (sandy loam and sandy) SaLo Sa LoSa
* 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). cite
* 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 < 6000°C/y), high heat Stress (4000°C/y < GDD < 6000°C/y). cite

**Data into category:** The categorical variables were classified as follows: (1) climate types were divided into four categories—equatorial, arid, warm temperate and boreal;

**Create majorly 3-4 zones maxi----climatic zones and see what happen within--------**

**Statistics**

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### **Publication bias and sensitivity (Joshi et al., 2023)**

The publication bias is classically conducted using a funnel plot analysis, but many studies did not rovide sample variance information required to create meaningful funnel plots. Therefore, a istogram was constructed to check the distribution of all individual effect sizes in the dataset to test for vidence of publication bias (Basche & DeLonge, 2017; Gurevitch et al., 2001; Thapa, Mirsky, et al., 2018). We also conducted a Jacknife sensitivity analysis to determine the sensitivity to any given study and hence, the robustness of the analysis (Philibert et al., 2012; Thapa, Mirsky, et al., 2018). During Jacknife analysis, each study was assigned a unique study ID and data from one of the studies was excluded from the database in each calculation.

Table 1: Environmental variables (in bracket are abbreviations)

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Indicators | Unit | Resolution |
| Soil properties | Soil texture | % | 250 m |
| pH |  | 250 m |
| soil organic carbon (SOC) | g/kg | 250 m |
| Soil Olsen phosphorus concentrations (phosphorus) | mg/kg | 1000 m |
| Bulk density (bd) | kg/dm³ | 250 m |
| Terrain | Slope | % | 0.0083° |
| Digital elevation model (dem) | m | 0.0083° |
| Geormorphological landform |  | 0.0083° |
| Climate | Growing degree days for maize (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for wheat (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for rice (GDD\_maize) | ° C | 0.0083° |
| Growing degree days for soybean (GDD\_maize) | ° C | 0.0083° |
| Aridity index (aridity) | °C/y | 0.0083° |

**CONTEXT Yield increase or decrease?**

* The prevailing environmental conditions of a region have the greatest inﬂuence on carbon sequestration and, as a result, crop yields
* Recent global analysis of NT-induced changes in soil C and crop yield based on 260 and 1970 paired studies, respectively, revealed that compared to CT, conservation agriculture beneﬁts arid regions the most by achieving a win–win outcome of increased C sequestration and crop yield. In more humid areas, only SOC gains are likely to occur, with no effect on crop yield, whereas in some colder areas there will be a negative impact on both SOC and yield [55].
* Increased SOC can lead to a higher crop yield, which can be attributed to increased plant available water holding capacity and N availability, particularly in N-deﬁcient soils. While a critical SOC threshold of 2% is established for sustainable crop production in temperate regions and about 1% in tropical regions [60], it would be worthwhile to investigate the minimum critical SOC threshold for cereals and other rotational crops in Western Australia’s Mediterranean climate.

Plan

address crises of soil health, biodiversity, and food security to sustain food production

* Introduce
* regenerative agriculture
* Give key example
* Show that effect size globally var across those and suggest why …. Here report key factors affecting such change in ES pattern
* Show limitation that they reported just for too numbers of environmental variables
* Here we will consider a broader range of EV and see how they vary to able to present a synthesis for decision making

Why my study is necessary:

* Given the paucity of studies where the alleles and mutations involved in adaptation in natural populations have been identified, we suggest that it is not yet possible to reach a general consensus on the subject of the distribution of effect sizes.

Objective

* Our goal is to give a broad overview of how the major mechanisms of evolution, i.e. natural selection, genetic drift, mutation and migration might influence the distribution of effect sizes of adaptive substitutions. We hope to motivate further theoretical and empirical study into the many ways in which the genetics and ecology of natural populations and species can influence the effect sizes of adaptive substitutions, and to encourage a consideration of these factors in future work.
* Our review extends the idea expressed by Remington [[**18**](https://royalsocietypublishing.org/doi/10.1098/rspb.2015.3065#RSPB20153065C18)] that there is no ‘one size fits all’ expectation for the distribution of effect sizes, and examines a range of factors that are expected to influence the distribution of effect sizes for adaptive substitutions.
* This paper describes in more detail the different hereditary and **environmental** **factors** that….
* The effectiveness of AMF at aggregating soil can therefore depend on a range of factors, whose individual effects cannot always be disentangled. To date there are several narrative reviews addressing AMF and soil aggregation (e.g. Oades [1993](https://link.springer.com/article/10.1007/s11104-013-1899-2#ref-CR62); Rillig and Mummey [2006](https://link.springer.com/article/10.1007/s11104-013-1899-2#ref-CR69); Six et al. [2004](https://link.springer.com/article/10.1007/s11104-013-1899-2#ref-CR75); Tisdall [1994](https://link.springer.com/article/10.1007/s11104-013-1899-2#ref-CR77)). Here we aim to quantitatively synthesize the importance of experimental settings and multiple biotic and abiotic factors for the effect of inoculation with AMF on soil macroaggregates.
* In general, adverse effects of accelerated soil acidification have been confirmed on soil compaction, the impedance of root growth, inhibition of micronutrients’ uptake, loss of N, and reduction of crop yield. Although NT has been widely reported to decrease the soil pH, divergent results have also been reported at different site-specific conditions. Thus, quantifying the effects, principal factors, and possible consequences of NT on soil acidification are crucial to understanding the pathway or/and mechanisms to sustaining agro-ecosystem services. Therefore, a global meta-analysis was conducted to understand: (i) The response of the soil pH and its variations among different conditions, (ii) the relative importance of factors affecting changes in soil pH, and (iii) relationships between soil pH and soil properties under NT.

# Results

# Overview of the data base (Pittel et al., 2015, de la Cruz 2023)

Data used in the meta-analysis are summarized in Table 1. In total, the overall crop category included 678 studies and 6005 observations following removal of outliers, representing 50 crops and 63 countries. Due to the large number of input variable combinations analyzed, ﬁgures with more than two levels of sub-categorization are provided as Supplementary Material (Supplementary Figs. 7–9). The number of observations in each crop category followed the order of wheat (29%), maize (27%), and legumes (18%), while the categories of rice, miscellaneous (mostly horticultural), and root crops had relatively few observations (Table 1). The dataset was dominated by studies from North America, followed by Asia and then Europe, while South America, Africa, and Australia and New Zealand contributed the least number of observations (Supplementary Fig. 10).

Table 1: Summary statistics of the data used in the meta-analysis. AG: agroforestry, CC: cover crop, NT: no-tillage, OF: Agroforestry. Aridity index are presented as mean (± standard deviation)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop Group | n | Studies | AF | CC | NT | OF | Arid | Continental | Temperate | Tropical | Aridity index |
| Overall | 10 002 | 732 | 783 | 1 029 | 7 622 | 568 | 1 716 | 3 396 | 3 774 | 1 111 | 0.65 (± 0.30) |
| Maize | 3 620 | 314 | 496 | 486 | 2 467 | 171 | 271 | 1 437 | 1 237 | 674 | 0.69 (± 0.25) |
| Wheat | 2 416 | 271 |  | 87 | 2 111 | 218 | 727 | 664 | 987 | 38 | 0.54 (± 0.29) |
| Rice | 486 | 48 |  | 53 | 428 | 5 | 27 | 14 | 338 | 103 | 0.96 (± 0.35) |
| Soybean | 937 | 121 |  | 20 | 899 | 18 | 38 | 561 | 325 | 13 | 0.79 (± 0.21) |
| Cereal | 1 203 | 136 | 169 | 7 | 942 | 85 | 354 | 507 | 313 | 29 | 0.54 (± 0.30) |
| Cash crop | 320 | 37 | 22 | 96 | 198 | 4 | 49 |  | 263 | 8 | 0.78 (± 0.30) |
| Vegetables, fruits and others | 1 020 | 120 | 96 | 280 | 577 | 67 | 250 | 213 | 311 | 246 | 0.58 (± 0.31) |
|  |  |  |  |  |  |  |  |  |  |  |  |

# Overall effect size by regenerative agriculture practices, crop groups, soil properties,

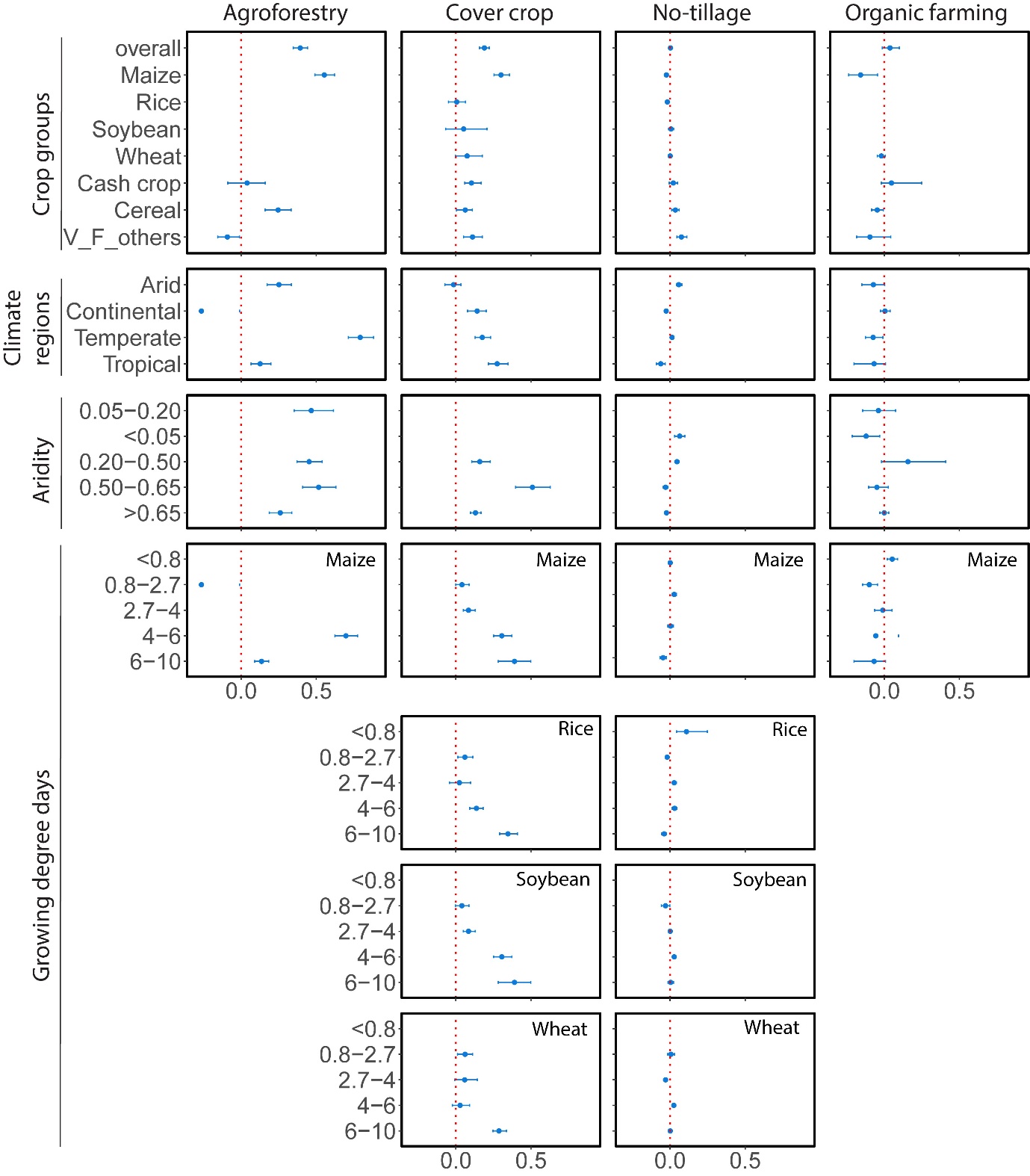
# terrain and climatic variables

# 

# Figure: Distribution of effect size between regenerative agriculture practices, crop groups, soil properties, terrain and climatic variables (RAP: Regenarative agriculture practices, P: Phosphosurs, BD; bulk density, DEM: digital elevation model, GDD: growing degree days)

# Effect size distribution across climate variables for different regenerative agriculture

# practices



# Figure: Distribution of effect size between regenerative agriculture practices, crop groups, soil properties, terrain and climatic variables (RAP: Regenarative agriculture practices, P: Phosphosurs, BD; bulk density, DEM: digital elevation model, GDD: growing degree days)

A screenshot of a graph

Description automatically generated

# Figure: Distribution of effect size between regenerative agriculture practices, crop groups, soil properties, terrain and climatic variables (RAP: Regenarative agriculture practices, P: Phosphosurs, BD; bulk density, DEM: digital elevation model, GDD: growing degree days)

De la Cruz: As previously mentioned, de Ponti et al. (2012) specified that the gap between individual organic and conventional crop yields is highly contextual to the region and crop group.

# Effect size distribution across terrain variables for different regenerative agriculture

# practices

De la Cruz: As previously mentioned, de Ponti et al. (2012) specified that the gap between individual organic and conventional crop yields is highly contextual to the region and crop group.

# Effect size distribution across soil properties for different regenerative agriculture

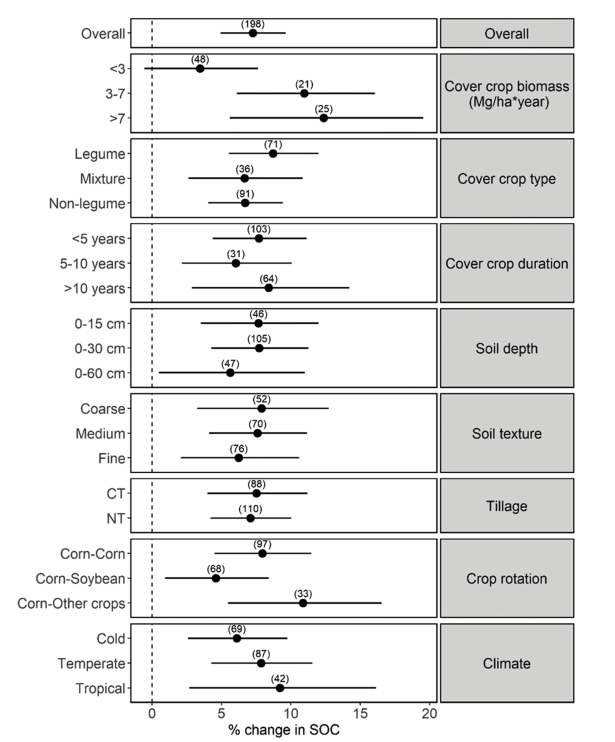
# practices

De la Cruz: As previously mentioned, de Ponti et al. (2012) specified that the gap between individual organic and conventional crop yields is highly contextual to the region and crop group.

**Statistics**

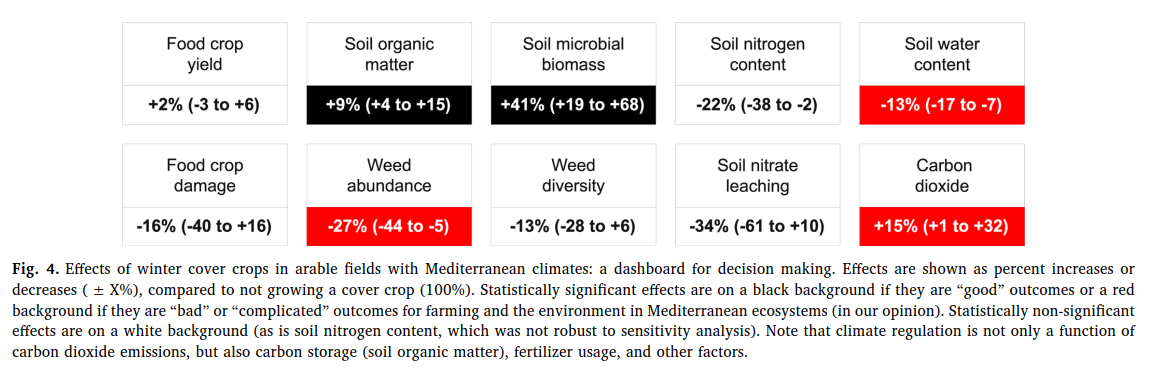
**Stepwise multiple linear regression with PCA : 2.2.4 Stepwise multiple linear regression Joshi et al**

**Joshi et al., 2023**



* **Final output: Dashboard of the ES distribution across the factors for each Regenerative Agriculture practice**

Shackelford, G.E., Kelsey, R. and Dicks, L.V., 2019. 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*, p.104204.



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