Temperate Regenerative Agriculture; a win-win for soil carbon and crop yield?

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Analysis

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Abstract

Regenerative Agriculture proposes to contribute to climate change mitigation and increased food production through improved yields by building soil organic carbon (SOC). We examine three Regenerative practices: reducing tillage intensity, cover cropping and including a grass-based phase in arable rotations (ley-arable systems). Our Bayesian meta-analysis of

195 paired SOC and crop yield observations from published studies finds statistically significant increases in SOC concentration for reduced tillage intensity (0.06 g C.100g^{-1}) and ley-arable systems (0.05 g C.100^{-1}g per year of ley) compared to conventional practice over an average study duration of 15 years, but no effect of cover crops. None of these practices come at a cost to yield during cropping years. However, we find no evidence of a win-win between soil carbon sequestration and enhanced agricultural productivity. Further, the small magnitude of SOC increases suggests a limited role for these Regenerative practices in climate change mitigation strategies in temperate regions.

Introduction

Regenerative Agriculture aims to increase soil organic carbon (SOC) alongside continued food production through adoption of beneficial management practices[1]. This narrative is rapidly gaining popularity among land managers, policy makers, NGOs and corporates[2-4], in part due to the dual importance of soil carbon sequestration in climate change mitigation[5,6] and improving soil health[7]. There have been limited studies of whole-system adoption of Regenerative Agriculture in temperate regions, although substantial evidence exists for individual management actions now considered regenerative, including no or reduced tillage, using cover crops and ley-arable rotations (Table 1). However, a knowledge gap exists as to the dual benefits (climate change mitigation and food production) associated with these different management practices. This is in part due to the fact that syntheses of the SOC and crop yield impacts of adopting these practices using paired observations is needed to determine both their utility in greenhouse gas mitigation strategies and appeal to land managers.

Here, we investigate the influence of three regenerative practices (reduced tillage intensity, cover cropping and ley-arable systems, Table 1) on SOC and crop yield in temperate arable systems, to test the hypothesis that Regenerative Agriculture can increase both soil carbon and agricultural productivity in these regions. We assemble a database of relevant studies conducted in regions with a temperate oceanic climate (Köppen-Geiger Cfb) using systematic review methods. We use this to parametrise a Bayesian multivariate meta-analysis of SOC and yield which includes the level of adoption of these three regenerative practices as predictors. We aimed to evaluate the suitability of these regenerative practices for inclusion in climate change mitigation strategies in these regions and to further understand the dynamics affecting the relationship between SOC and yield in arable systems.

Table 1. Definitions and selected benefits and limitations of Regenerative Agriculture practices investigated in this systematic review

Intervention	**Synonyms†**	**Definition**	**Benefits**	**Limitations**
No- or reduced-tillage	Direct drilling, conservation tillage, minimum tillage	Absence or reduction of mechanical soil disturbance in seedbed preparation[8]	Improved soil structure and biological activity, decreased risk of soil erosion[9], improved water quality[10]	Can compact soils, increasing nitrous oxide emissions, limiting SOC gain for equivalent soil mass, and risk of waterlogging. Increased requirement for herbicides for weed control[9].
Cover crops	Catch crops, green manure	Inclusion of temporary fast-growing plants to cover the soil between cash crops[11]	Reduce nitrogen leaching[12], enhance soil microbiota[13]	Inclusion of legumes can increase nitrous oxide emissions[14], can require cultivation or herbicides to terminate
Ley-arable	Integrated crop-livestock, mixed farming	Temporary grass-based ley included for one or multiple consecutive years within arable rotation[15]	Ley phase builds fertility for following arable cash crops and can provide livestock fodder[16-19]	No arable crop and often lower income from ley phase of rotation compared to continuous arable cropping, which could displace production thereby increasing emissions elsewhere (leakage). Requires cultivation or herbicides to terminate.

† Although no/reduced tillage and use of cover crops are both components of conservation agriculture, conservation agriculture is not a synonym for either of these practices in isolation.

Results

Our systematic review identified 23 studies (18 articles) that measured the effect of changing tillage intensity on SOC and yield (Fig S1), with data extracted from a total of 106 tillage intensity treatments (Fig S2). We found that converting from conventional full-inversion tillage to no tillage increased SOC concentration by 0.06 g C.100g^{-1} (95% Credible Intervals 0.00 to 0.12), and reduced-tillage by 0.09 (0.03, 0.15), over an average study duration of 15 years (Table 2, Fig 1a), without negatively impacting crop yield (95% Credible Intervals of effect size include 0, Table 2, Fig 1b).

Of the 12 studies (nine articles) that investigated incorporating cover crops into arable rotations (Fig S1), resulting in 79 observations of SOC and yield, we found no effect of cover cropping in every year of an arable rotation on SOC (95% Credible Intervals -0.00 to 0.14 g C.100g^{-1}) or yield (Table 2, Fig 1c-d) compared to when no cover crops were present.

Thirteen studies (11 articles) reported SOC and yield effects of integrating a grass-based ley phase into arable rotations (Fig S1), giving 70 data points with ley duration ranging from zero to six years within the rotation (Fig S4). Inclusion of a one-year ley phase increased SOC concentration by 0.05 g C.100g^{-1} (95% Credible Intervals 0.03 to 0.08 Table 2, Fig 1e) after 15 years compared with an arable-only rotation. This effect size could be multiplied by ley duration in years to estimate the impact of longer ley phases on soil carbon. Arable crop yields were not affected by the inclusion of a ley-phase in the rotation (95% Credible Intervals of effect size include 0, Table 2, Fig 1f). However, because inclusion of a grass-based ley in a rotation results in complete absence of a cash crop yield in those years, the total output of arable crop (e.g. tonnes of cereal) of the overall rotation is reduced in proportion to the duration of the ley-phase in ley-arable systems.

We also found that differences in study duration and absolute latitude had no effect on SOC concentration or crop yield, and soil clay content (%) did not significantly predict SOC concentration (Table 2). SOC concentration decreased by 0.05 g $C.100g^{-1}$ (95% CI -0.09 to -0.02, Table 2) per cm of increased sampling depth, included as a predictor in the analysis to control for the different sampling depths between studies which ranged from 5-30 cm. Baseline SOC concentration was not a significant predictor of endline SOC (95% Credible Intervals -0.04 to 0.30, Table 2).

Sensitivity analyses

We ran five iterations of our analysis to account for different levels of data availability and quality (see Methods), to test the sensitivity of the EIBI results reported above. Use of multiple imputation where standard errors were missing from observations did not affect the significance or direction of results, i.e. these are consistent with the analysis of a smaller dataset containing only observations where standard errors were reported (EP, Table 2). Where baseline SOC values were reported in studies, this was a significant predictor of endline SOC (EIBP, Table 2), with an increase in endline values of 0.76 g $C.100g^{-1}$ (95% Credible Intervals 0.38 to 1.10) for every 1 g $C.100g^{-1}$ increase in baseline SOC. However, this relationship was not preserved when missing baseline SOC values were imputed (EIBI, Table 2), suggesting the imputation process did not perform sufficiently well for use on this predictor. The EIBP analysis also did not find a significant effect of reduced tillage or soil sampling depth, which could be a feature of the data in this smaller number of observations or due to SOC baseline explain this variation in the data instead. Our finding of an increase in SOC when a ley-phase is included in arable rotations was robust to exclusion of studies with low or unclear validity (CA), but the positive effects of no- and reduced tillage on SOC were not preserved (Table 2).

SOC-yield relationship

Despite finding a positive correlation between SOC and yield, our univariate analysis of crop yield did not identify any significant interactions between interventions and SOC (Table S8); the relationship between SOC and yield did not differ when each intervention was adopted or between interventions (Fig 2). We found a significant residual correlation between SOC concentration and crop yield in the EP model (i.e. after all other predictors were accounted for), but this was not retained in the other fully parametrised analyses (Table 2).

Discussion

Results from our meta-analysis demonstrate that some Regenerative Agricultural practices currently adopted in the temperate biome can significantly enhance SOC without negatively impacting crop yield during years with arable crops. Our finding that reducing tillage intensity increases SOC matches that of previous European[20,21], temperate[8] and global[22] analyses. Reduced soil disturbance can protect SOC from degradation through enhanced soil aggregation and lower soil temperatures[23]. However, it must be noted that accumulation of crop residues at the soil surface can also contribute to increased soil carbon concentration when only shallow sampling depths (≤30 cm) are considered[24], as here. This can lead to an overestimation of the SOC gains of reducing tillage intensity, with evidence of a redistribution of SOC within the soil profile and smaller overall increase when deeper soil samples are considered[9,24,25]. Previous studies have shown that reduced tillage intensity can negatively impact crop productivity through lower soil temperatures and increased compaction which can impair root growth, drainage and aeration, with yield gains typically only found in water-limited conditions in dry climates due to the moisture retention benefits of surface crop residues[23,26,27]. However, contrary to these previous European analyses[20,28], we do not find a trade-off between increased SOC and reduced crop yield following a reduction in tillage intensity in temperate oceanic regions. Rather our findings are in line with those of Sun, et al. [27] that conservation agriculture can increase SOC without changing crop yield in humid regions.

We found no effect of cover cropping on SOC or yield, which is concordant with other work from Europe[20]. Cover crops can increase SOC through increasing plant residue inputs to soil, although this effect has been found to lessen for studies i) with greater rates of fertiliser application, ii) at higher latitude and lower temperatures, which limit cover crop growth, and iii) when cover crops used were grass-based rather than legume or mixed, possibly due to a higher C:N ratio increasing the time taken to build SOC[11,12,29]. These factors could all contribute to explaining why we did not find an effect of cover crops on SOC in temperate oceanic arable systems. Leguminous cover crops could confer a cash crop yield benefit by enhancing soil fertility through nitrogen fixation, and non-legume covers by enhancing retainment of existing soil nutrients, but it is also possible that cover crops compete with the following cash crops for nutrients particularly if not terminated correctly. Previous syntheses have reported inconsistent effects of cover crops on yield within the commonly-used categories of legume, non-legume and mixed[12]; further work is required to adequately explain differences in reported trends.

Our finding that including a grass-based ley phase in temperate oceanic arable systems increases SOC is likely due to a combination of i) increased plant residue inputs, particularly root litter from the better-established root systems in multi-year leys of perennial grasses and forbs compared to annual cash crops, ii) temporary cessation of cultivation protecting SOC from degradation, and iii) greater development of roots and soil microflora conferring improved stability of soil aggregates which further protects SOC from degradation during cultivation in the arable phase[30,31]. Conversion of cropland to grassland typically increases SOC[32-34], meaning ley-arable systems are likely to fluctuate between increasing SOC during the ley phase and declines during the arable phase, resulting in an intermediate that is nevertheless higher than continuous cropping[15,30]. We had expected to find an increase in cash crop yields following a ley-phase in arable rotations, due to the long-established fertility building properties of temporary leys resulting in their current widespread adoption in organic arable systems[15-18]. It is likely we did not identify this trend here due to the confounding effect of study fertiliser applications; the positive association between crop yield and duration of the preceding ley has been found to disappear as crop fertiliser applications increase[35,36]. Although we did not find a negative effect of ley integration into arable rotations on subsequent cash crop yield, ley-arable systems require a proportion of total cropland to be taken out of cash crop production each year. This potentially results in compensatory cultivation elsewhere leading to overall SOC losses[37], requiring a reorientation of livestock feeding to reduce the area of cash cropland per year required[38].

Overall, we do not find evidence to support a synergy between increased soil carbon and crop yield when adopting the Regenerative Agriculture practices considered here in temperate oceanic arable systems. We focused solely on soil carbon as an indicator of the climate change mitigation potential of reduced tillage intensity, cover cropping and ley-arable systems, in order to test our hypotheses relating to the relationship between SOC and yield. However, there are other factors relevant to the overall climate impact of these practices not considered here, including: i) soil greenhouse gas emissions, for example reduced tillage and cover cropping can increase soil N_2O emissions[9,14], ii) machinery operations, which, for example, decrease with reduced tillage, and iii) requirements for manufactured inputs, including fertilisers and pesticides. Future work should build on our findings to conduct full greenhouse gas inventories of Regenerative Agriculture practices to determine their suitability for inclusion in climate change mitigation strategies. Furthermore, our systematic review addressed individual interventions that can be part of a Regenerative Agriculture approach, rather than comparing ‘regenerative’ systems that simultaneously implement multiple interventions with ‘conventional’ systems. There is currently a paucity of studies specifically evaluating ‘regenerative’ systems, although our analysis of the dataset in ‘raw’ form enabled us to best represent studies that implemented multiple interventions factorially. A further issue with considering Regenerative Agriculture practices individually rather than in combination is that it masks the potential difficulties of implementing these simultaneously in a real-world context as part of a regenerative system. For example, terminating cover crops or a ley phase in arable rotations requires either tillage or use of a broad-spectrum herbicide (Table 1), limiting the adoption of reduced tillage alongside these measures by organic farmers due to the pesticide-free requirements of organic certification standards.

Conclusion

We identify two Regenerative Agriculture practices which increase soil carbon concentration without negatively impacting crop yield in temperate arable systems - reducing tillage intensity and incorporating leys into rotations. This maintenance of yields in arable cropping years has potential to increase the appeal to land managers of these practices. The loss of crop production during the grass-phase of ley-arable rotations limits potential for increased adoption of this practice without compensatory cultivation elsewhere or a restructuring of livestock feeding systems in these regions. Notwithstanding the fact that there are other advantages to reducing tillage, adoption of cover crops and ley-arable rotations, we find no clear evidence supporting the drive to promote these regenerative practices solely for climate change mitigation purposes. While not the win-win that some suggest Regenerative Agriculture can offer, based on current evidence, future work could build on the results of our analysis and the evidence base assembled here to conduct full greenhouse gas inventories to assess the overall mitigation potential of Regenerative Agriculture. Further primary research should investigate the potential synergies and trade-offs between implementing multiple regenerative practices simultaneously.

Methods

The evidence base

We followed the Collaboration for Environmental Evidence guidelines[39] to address the systematic review question "What are the impacts on soil carbon and crop yield from reducing tillage, adopting cover crops and integrating leys into rotations in temperate oceanic arable systems?", using the Population, Intervention, Comparator, Outcome and Location (PICOL) framework (Table S1). Previously, Haddaway, et al. [40] systematically mapped the effects of a broad range of agricultural management practices on soil carbon in boreo-temperate systems, subsequently updated in part for tillage studies[8]. We utilised, expanded and updated these previous searches, focusing on tillage, cover crops and ley-arable interventions in temperate oceanic regions. Full details of our systematic review following the RepOrting standards for Systematic Evidence Syntheses[41] are given in the Supplementary Methods, building on the methods of Haddaway, et al. [8], Haddaway, et al. [40]. All data extracted from relevant studies is provided in Supplementary Table 1 and further supplementary files are available online[42].

We conducted searches in Web of Science, CAB Abstracts and Scopus (details in Table S2, Supplementary Methods 1.1) and screened records at title, abstract and full text levels using pre-determined inclusion and exclusion criteria (Table S3), with consistency checking between reviewers (Supplementary Methods 1.2). Data from relevant studies was extracted to a spreadsheet (Supplementary Table 1, Supplementary Methods 1.3), and assigned a critical appraisal score reflecting the study quality (Table S4). For studies that present SOC and yield data for multiple sampling dates, we extracted only the most recent data (i.e. study 'endline'). We also extracted SOC baseline (i.e. pre-intervention) measurements, but no studies in our systematic review present baseline data for yield. Where SOC data were presented in studies as stocks ($t.ha^{-1}$) we converted these to concentration ($g.100g^{-1}$) using soil bulk density (Table S5). We extracted within-treatment standard errors for study SOC and yield estimates where available. Where a different measure of within-treatment variability was presented, these were converted to standard error (Table S5). If measures of variability presented were between-treatment only, these were not extracted. Where desired data was missing from articles (Table S6), we attempted to contact the corresponding author with a request for data (Supplementary Methods 1.4).

Our systematic review resulted in a database of 30 articles containing 40 studies across 10 countries with temperate oceanic regions (Fig 3, S1). From this, we extracted 195 paired observations of SOC and crop yield across tillage, cover crop and ley-arable interventions for quantitative meta-analysis (Supplementary Data 1).

Meta-analysis

We fitted Bayesian multivariate hierarchical (i.e. random effects) meta-analyses using the *brms* package in R version 4.0.3[43-46]. Our R code is available online[42] and further details of the analysis approach are given in the Supplementary Methods. All models fitted explained a large proportion of variation in the data, with Bayes R^2 ranging from 0.85-0.98 and 0.44-0.94 for the full model and fixed effects respectively (Table 2).

We analysed the 'raw' data extracted from studies in our systematic review (i.e. one row of data per study treatment), rather than computing effect size metrics for each study (i.e. one row per control-intervention comparison). This was because i) within each response variable (SOC concentration, $g.100g^{-1}$, and crop yield, $t.ha^{-1}$) data across all treatments and studies are directly comparable on the same scale, ii) the cover crop and ley-arable interventions are best expressed as continuous variables, iii) some studies include multiple interventions of interest, and iv) the outputs from the model are easily understood and biologically meaningful. Because some studies contained data on more than one intervention, we analysed the three interventions together, rather than fitting individual models. Combining the analyses in this way is robust to Simpson's Paradox because 'sub-groups' of data corresponding to each intervention were used to estimate separate intervention-specific effects rather than one overall effect and the hierarchical nature of the analysis through inclusion of Study ID as a random effect prevented control treatments from being isolated from intervention treatments. We fitted the following models together in a multivariate analysis:

$$SOC_E \sim Tillage + Cover\ crop + Ley + Duration + Latitude + Clay + Depth + SOC_B + (1|Unique\ study\ ID)$$

$$Yield_E \sim Tillage + Cover\ crop + Ley + Duration + Latitude + Crop + (1|Unique\ study\ ID)$$

where

- SOC_E, 'endline' estimate of soil organic carbon concentration (g.100g^{-1}), accounting for its standard error,
- $Yield_E$, 'endline' estimate of crop yield (t.ha^{-1}), accounting for its standard error,
- *Tillage*, categorical variable of tillage regime; conventional tillage (reference category), reduced tillage or no tillage, with variables dummy coded,
- *Cover crop*, frequency of cover crops in arable rotation, expressed as a proportion where 0 is no cover crops (reference) and 1 is cover crops present every year,
- *Ley*, duration (years) of the ley-phase of the arable rotation (reference = 0, i.e. arable-only rotation),
- *Duration*, total duration of study (years), from implementation of treatment interventions to the most recent data presented in the original article,
- *Latitude*, absolute Latitude of the study site, in decimal degrees,

- *Clay*, soil clay content (%) of the study site,
- *Depth*, soil sampling depth (cm) soil to measure SOC,
- SOC_B, true baseline, i.e. pre-intervention, estimate of soil organic carbon concentration (g.100g^{-1}),
- *Crop,* crop harvested to give $Yield_E$ measurement,
- *Unique study ID*, included as a random effect to account for the hierarchical structure of the data

Although stocks (t.ha^{-1}) are the most relevant unit of SOC for assessing carbon sequestration and therefore greenhouse gas mitigation potential, this depends both on sampling depth and soil bulk density which differ between studies. Further, there was limited availability of treatment-specific bulk density measurements in studies (Table S6) to transform SOC concentrations (more-commonly reported) to stocks. We therefore use SOC concentration (g.100g^{-1}) in our analysis to allow us to investigate the relationship between crop yield and SOC across studies. For studies that investigated different tillage regimes, depth-stratified soil carbon values were commonly given for each treatment, with only one corresponding yield value. Therefore, to perform our multivariate analysis, we averaged soil carbon to 30 cm (weighted by the soil thickness of each stratified sample where this differed), such that each treatment had only one row of data. Because not all studies sampled soil to 30 cm deep, sampling depth was included as a predictor in the meta-analysis to account for studies with shallow sampling only (e.g. 10 cm). We did not investigate whether different tillage regimes changed the depth distribution of soil carbon as this was not relevant to the hypotheses we were seeking to test, although this has recently been empirically addressed elsewhere[24,25]. We chose to represent *Ley* duration in years, unlike *Cover crops* where a proportion was used, to capture the duration-dependence of sward and root development during the ley phase. Where missing in the original article, clay data were extracted from the WISE30sec harmonised global soil property database[47] using study site coordinates. We centred the Duration, Clay, Depth, Latitude and SOC_B predictors around their respective means, so that the model output intercept was biologically meaningful and corresponded to conventional practice (i.e. conventional tillage and no cover cropping or ley phase in arable rotation).

We set weakly informative normal prior distributions (mean 0, standard deviation 1) for the SOC and Yield responses. Details on model sampling are given in Table S7. We checked model convergence using the Rhat parameter and ensured effective sample size measures were sufficiently large[48]. Model non-convergence was addressed by increasing the number of iterations for sampling and divergent transitions were addressed by decreasing the sampler step size[49]. We assessed the statistical significance of fixed effect model predictors (i.e. all apart from Unique study ID) based on whether their 95% credible intervals included zero and used Bayes R^2 to estimate the proportion of variation explained by the overall model and fixed effects only[50].

We plotted the conditional effects of $Tillage$, $Cover\ crop$ and Ley on SOC_E and $Yield_E$, showing trends for individual predictors where all other model predictors are at the reference category. We also displayed the raw SOC and Yield data from the underlying studies for each intervention using the *forestplot* package[51]. To calculate the overarching estimates used in the summary section of these forest plots, we subset the data so only studies looking at that intervention were included, then fit a simple univariate *brm* model:

$$response \sim intervention + (1|Unique\ study\ ID)$$

where $response$ is SOC_E or $Yield_E$ and $intervention$ is one of $Tillage$, $Cover\ crop$ or Ley. The large amount of heterogeneity across studies in our dataset means it would be challenging to detect publication bias, so we chose not to generate funnel plots as their results and corresponding tests would very likely be misleading in either direction.

To investigate if the relationship between SOC and Yield changed between interventions, we fitted a univariate model:

$$Yield_E \sim Tillage^{*}SOC_e + Cover\ crop^{*}SOC_e + Ley^{*}SOC_e + \ Crop + (1|Unique\ study\ ID)$$

All parameters are the same as defined above, except SOC_e which is the 'endline' estimate of soil organic carbon concentration (g.100g^{-1}) without accounting for its standard error, due to the modelling difficulties of incorporating this in the predictor. Conditional effects plots of the interaction terms allowed us to identify whether the slope of the SOC-yield regression line differed between adoption of each intervention.

Imputation and sensitivity analyses

Of the 195 paired observations of SOC and crop yield identified in our systematic review, 78 did not include a measure of within-treatment variability for SOC_E, 105 did not include a measure of within-treatment variability for $Yield_E$, and 116 did not include SOC_B. Overall, only 66 data had within-treatment standard errors presented or calculable for both SOC_E and $Yield_E$. Unless values are missing at random, discarding data with missing values risks biasing the meta-analysis[52]. We therefore used multiple imputation methods to fill missing values, which has the advantage of explicitly representing the variability associated with the imputation process in the meta-analysis[53]. We used the *mice* package in R, which uses chained equations to impute missing values, to generate 10 imputed datasets before model fitting in *brms*[54]. Due to the large number of missing values in our dataset, we ran the analysis four times with different data availability, to test the sensitivity of the results to the level of imputation. In addition, we used the critical appraisal scores assigned during our systematic review (Table S4, Supplementary Methods section 1.3) to run a further analysis excluding studies with fewer than three true replicates or that did not specify treatment allocation (i.e. were not split-plot, blocked, randomised, or equivalent), to test the sensitivity of our results to study quality:

1. EP: SOC_E and $Yield_E$ standard errors available, SOC_B not included in model as predictor (66 data from 16 studies, average duration 8.6 years)
2. EI: SOC_E and $Yield_E$ standard errors imputed where missing, SOC_B not included in model as predictor (195 data from 40 studies, average duration 12.5 years)
3. EIBP: SOC_E and $Yield_E$ standard errors imputed where missing, SOC_B available from study and included as predictor (79 data from 14 studies, average duration 12.5 years)
4. EIBI: SOC_E and $Yield_E$ standard errors imputed where missing, SOC_B imputed where missing and included as predictor (195 data from 40 studies, average duration 15.1 years)
5. CA: Same as (4), but data from studies with low or unclear validity based on critical appraisal scores excluded (144 data from 25 studies, average duration 12.5 years)

We use the results from EIBI throughout the paper and in Figure 1. We present model outputs from all analyses in Table 2 for comparison and discuss their sensitivity to data availability and quality in the Results.

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Supporting Information

Supplementary Methods. Further details of systematic review, Bayesian meta-analysis methods and forest plots of raw data extracted from studies.

Supplementary Data. Full dataset of extracted values from relevant studies in systematic review (raw data, with additional calculations, if any, recorded).

References

1 Moyer, J., Smith, A., Rui, Y. & Hayden, J. Regenerative Agriculture and the Soil Carbon Solution. (Rodale Institute, 2020).

2 Burgess, P. J., Harris, J., Graves, A. R. & Deeks, L. K. Regenerative Agriculture: Identifying the Impact; Enabling the Potential. (Report for SYSTEMIQ, Bedfordshire, UK: Cranfield University, 2019).

3 Giller, K. E., Hijbeek, R., Andersson, J. A. & Sumberg, J. Regenerative Agriculture: An agronomic perspective. *Outlook Agric* **50**, 13-25, doi:10.1177/0030727021998063 (2021).

4 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**, doi:10.3389/fsufs.2020.577723 (2020).

5 Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**, 1-22, doi:10.1016/j.geoderma.2004.01.032 (2004).

6 Poulton, P., Johnston, J., Macdonald, A., White, R. & Powlson, D. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Glob Chang Biol* **24**, 2563-2584, doi:10.1111/gcb.14066 (2018).

7 Bradford, M. A. *et al.* Soil carbon science for policy and practice. *Nature Sustainability* **2**, 1070-1072, doi:10.1038/s41893-019-0431-y (2019).

8 Haddaway, N. R. *et al.* How does tillage intensity affect soil organic carbon? A systematic review. *Environmental Evidence* **6**, doi:10.1186/s13750-017-0108-9 (2017).

9 Powlson, D. S. *et al.* Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* **4**, 678-683, doi:10.1038/nclimate2292 (2014).

10 Skaalsveen, K., Ingram, J. & Clarke, L. E. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil and Tillage Research* **189**, 98-109, doi:10.1016/j.still.2019.01.004 (2019).

11 Poeplau, C. & Don, A. Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. *Agric. Ecosyst. Environ.* **200**, 33-41, doi:10.1016/j.agee.2014.10.024 (2015).

12 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, doi:10.1111/gcb.14644 (2019).

13 Kim, N., Zabaloy, M. C., Guan, K. & Villamil, M. B. Do cover crops benefit soil microbiome? A meta-analysis of current research. *Soil Biology & Biochemistry* **142**, doi:10.1016/j.soilbio.2019.107701 (2020).

14 Muhammad, I. *et al.* Regulation of soil CO2 and N2O emissions by cover crops: A meta-analysis. *Soil & Tillage Research* **192**, 103-112, doi:10.1016/j.still.2019.04.020 (2019).

15 Lemaire, G., Gastal, F., Franzluebbers, A. & Chabbi, A. Grassland-Cropping Rotations: An Avenue for Agricultural Diversification to Reconcile High Production with Environmental Quality. *Environ Manage* **56**, 1065-1077, doi:10.1007/s00267-015-0561-6 (2015).

16 Elliot, R. H. *The Clifton Park System of Farming and laying down land to grass - a guide to landlords, tenants and land legislators*. Fourth edn, (Faber and Faber Limited, 1908).

17 Turner, N. *Fertility Farming*. (Faber & Faber Ltd, 1951).

18 Stapledon, R. G. & Davies, W. *Ley farming*. (Faber & Faber Ltd, 1948).

19 Martin, G. *et al.* Role of ley pastures in tomorrow's cropping systems. A review. *Agronomy for Sustainable Development* **40**, doi:10.1007/s13593-020-00620-9 (2020).

20 Sanden, T. *et al.* European long-term field experiments: knowledge gained about alternative management practices. *Soil Use and Management* **34**, 167-176, doi:10.1111/sum.12421 (2018).

21 Smith, P., Powlson, D. S., Glendining, M. J. & Smith, J. U. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. *Global Change Biology* **4**, 679-685 (1998).

22 West, T. O. & Post, W. M. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal* **66**, 1930-1946 (2002).

23 Huang, Y. *et al.* Greenhouse gas emissions and crop yield in no-tillage systems: A meta-analysis. *Agriculture, Ecosystems & Environment* **268**, 144-153, doi:10.1016/j.agee.2018.09.002 (2018).

24 Meurer, K. H. E., Haddaway, N. R., Bolinder, M. A. & Kätterer, T. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews* **177**, 613-622, doi:10.1016/j.earscirev.2017.12.015 (2018).

25 Xiao, L., Zhou, S., Zhao, R., Greenwood, P. & Kuhn, N. J. Evaluating soil organic carbon stock changes induced by no-tillage based on fixed depth and equivalent soil

mass approaches. *Agriculture, Ecosystems & Environment* **300**, doi:10.1016/j.agee.2020.106982 (2020).

26 Pittelkow, C. M. *et al.* When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156-168, doi:10.1016/j.fcr.2015.07.020 (2015).

27 Sun, W. *et al.* Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Glob Chang Biol* **26**, 3325-3335, doi:10.1111/gcb.15001 (2020).

28 Zavattaro, L. *et al.* Long-term effects of best management practices on crop yield and nitrogen surplus. *Italian Journal of Agronomy* **10**, 47-50, doi:10.4081/ija.2015.643 (2015).

29 Jian, J., Du, X., Reiter, M. S. & Stewart, R. D. A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology & Biochemistry* **143**, doi:10.1016/j.soilbio.2020.107735 (2020).

30 Soussana, J. F. *et al.* Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use and Management* **20, Suppl.**, 219-230, doi:10.1079/SUM2003234 (2004).

31 Conant, R. T., Paustian, K. & Elliott, E. T. Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications* **11**, 343-355, doi:10.1890/1051-0761(2001)011[0343:gmacig]2.0.co;2 (2001).

32 Guo, L. B. & Gifford, R. M. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* **8**, 345-360, doi:10.1046/j.1354-1013.2002.00486.x (2002).

33 Conant, R. T., Cerri, C. E. P., Osborne, B. B. & Paustian, K. Grassland management impacts on soil carbon stocks: a new synthesis. *Ecol. Appl.* **27**, 662-668, doi:10.1002/eap.1473 (2017).

34 Smith, P. Do grasslands act as a perpetual sink for carbon? *Glob Chang Biol* **20**, 2708-2711, doi:10.1111/gcb.12561 (2014).

35 Johnston, A. E. *et al.* Effects of one to six year old ryegrass-clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans (Vicia faba) grown on a sandy loam soil. *Journal of Agricultural Science* **122**, 73-89 (1994).

36 Rasmussen, J., Eriksen, J., Hansen, E. M. & Christensen, B. T. Carbon sequestration and residual effect of differently aged grass leys. *DJF Rapport, Markbrug* **137**, 40-43 (2008).

37 Carlton, R., Berry, P. & Smith, P. Impact of crop yield reduction on greenhouse gas emissions from compensatory cultivation of pasture and forested land. *International Journal of Agricultural Sustainability* **8**, 164-175, doi:10.3763/ijas.2009.0484 (2010).

38 Karlsson, J. O. & Röös, E. Resource-efficient use of land and animals—Environmental impacts of food systems based on organic cropping and avoided food-feed competition. *Land Use Policy* **85**, 63-72, doi:10.1016/j.landusepol.2019.03.035 (2019).

39 CEE. Collaboration for Environmental Evidence. Guidelines and Standards for Evidence synthesis in Environmental Management. Version 5.0. (2018).

40 Haddaway, N. R. *et al.* What are the effects of agricultural management on soil organic carbon in boreo-temperate systems? *Environmental Evidence* **4** (2015).

41 Haddaway, N. R., Macura, B., Whaley, P. & Pullin, A. S. (2017). ROSES for Systematic Review Reports.

42 Jordon, M. W. (2021). Supplementary Files for Systematic Review. DOI: 10.5281/zenodo.5517420

43 Bürkner, P.-C. brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software* **80**, doi:10.18637/jss.v080.i01 (2017).

44 Bürkner, P.-C. Advanced Bayesian Multilevel Modeling with the R Package brms. *THe R Journal* **10**, 395-411 (2018).

45 Stan Development Team. Stan Modeling Language Users Guide and Reference Manual. Version 2.27. (2019).

46 R Core Team. R: A language and environment for statistical computing. (R Foundation for Statistical Computing, Vienna, Austria, 2020).

47 Batjes, N. H. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. *Geoderma* **269**, 61-68, doi:10.1016/j.geoderma.2016.01.034 (2016).

48 Vehtari, A., Gelman, A., Simpson, D., Carpenter, B. & Bürkner, P. C. Rank-normalization, folding, and localization: An improved Rhat for assessing convergence of MCMC. *Bayesian Analysis*, 1-28, doi:10.1214/20-BA1221 (2020).

49 Stan Development Team. *Brief Guide to Stan's Warnings*, <https://mc-stan.org/misc/warnings.html> (2020).

50 Gelman, A., Goodrich, B., Gabry, J. & Vehtari, A. R-squared for Bayesian Regression Models. *The American Statistician* **74**, doi:10.1080/00031305.2018.1549100 (2019).

51 Gordon, M. & Lumley, T. (2020).

52 Weir, C. J. *et al.* Dealing with missing standard deviation and mean values in meta-analysis of continuous outcomes: a systematic review. *BMC Med Res Methodol* **18**, 25, doi:10.1186/s12874-018-0483-0 (2018).

53 Lajeunesse, M. J. in *Handbook of Meta-analysis in Ecology and Evolution* (eds Julia Koricheva, Jessica Gurevitch, & Kerrie Mengersen) Ch. 13, (Princeton University Press, 2013).

54 van Buuren, S. & Groothuis-Oudshoorn, K. mice: Multivariate Imputation by Chained Equations in R. *Journal of Statistical Software* **45**, 1-67 (2011).

55 Martin, A. C. *Thalloo Evidence-Mapping: A Jekyll Theme*, <https://github.com/AndrewIOM/thalloo> (2018).

Figure legends

Figure 1. Effects of interventions on SOC concentration and crop yield. Conditional effects of (**a-b**) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (**c-d**) cover cropping, proportion of years present in arable rotation, (**e-f**) ley-arable systems, length of ley phase within the arable rotation in years, for soil organic carbon (g.100g^{-1}) and cash crop yield (t.ha^{-1}) respectively for each intervention. Error bars show 95% Credible Intervals. Results from the EIBI analysis, see Methods for further details. Conditional effects show the model-fitted values for individual interventions when all other model predictors are at the reference category (i.e. conventional practice for the other interventions).

Figure 2. Differences in correlation between soil carbon and yield between levels of adoption of each intervention. Conditional effects of interactions between soil organic carbon (g.100g^{-1}) and (**a**) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (b) cover cropping, proportion of years present in arable rotation, (**c**) ley-arable systems, length of ley phase within the arable rotation in years, on cash crop yield (t.ha^{-1}). Error bars show 95% Credible Intervals. Results from univariate yield analysis using

EI data, see Methods for further details. Conditional effects show the model-fitted values for individual interaction terms when all other model predictors are at the reference category (i.e. conventional practice for the other interventions).

Figure 3. Systematic map. 40 relevant studies identified by systematic review process for inclusion in meta-analysis, created using the Thalloo framework [55]. Position of pie charts reflects study locations (degrees decimal coordinates), size of pie charts is proportional to the number of studies in that region (or the site when zoomed in online), and the colour of the chart segments shows the number of studies of each intervention (see legend). Inset shows southern Hemisphere studies. An interactive version of this evidence map with the accompanying study database is available online at https://oxlel.github.io/evidencemaps/oceanic_climates/

Figures

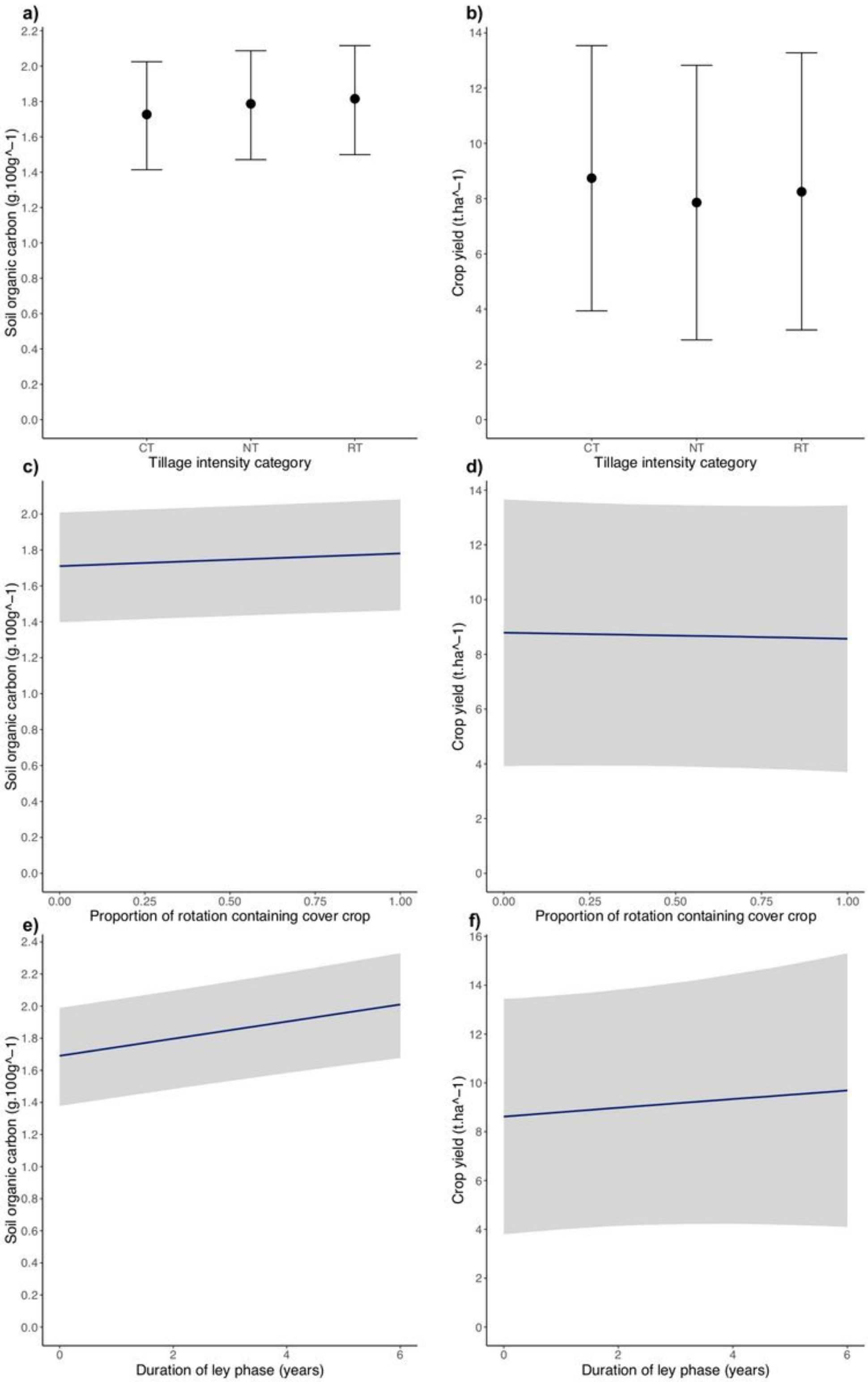

Figure 1

Effects of interventions on SOC concentration and crop yield. Conditional effects of (a-b) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (c-d) cover cropping, proportion of years present in arable rotation, (e-f) ley-arable systems, length of ley phase within the arable rotation in years, for soil organic carbon (g.100g-1) and cash crop yield (t.ha-1) respectively for each intervention. Error bars show 95% Credible Intervals. Results from the EIBI analysis, see Methods for further details. Conditional effects show the model-fitted values for individual interventions when all other model predictors are at the reference category (i.e. conventional practice for the other interventions).

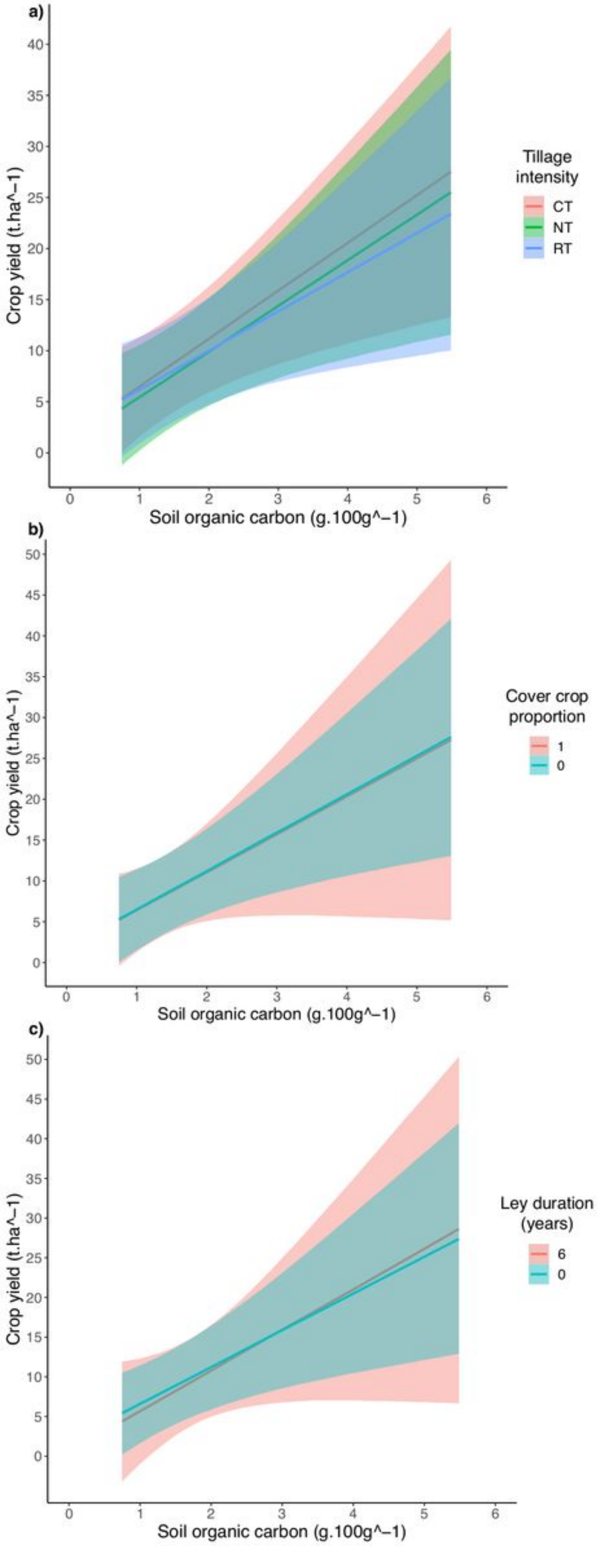

Figure 2

Differences in correlation between soil carbon and yield between levels of adoption of each intervention. Conditional effects of interactions between soil organic carbon (g.100g-1) and (a) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (b) cover cropping, proportion of years present in arable rotation, (c) ley-arable systems, length of ley phase within the arable rotation in years, on cash crop yield (t.ha-1). Error bars show 95% Credible Intervals. Results from univariate yield analysis using EI data, see Methods for further details. Conditional effects show the model-fitted values for individual interaction terms when all other model predictors are at the reference category (i.e. conventional practice for the other interventions).

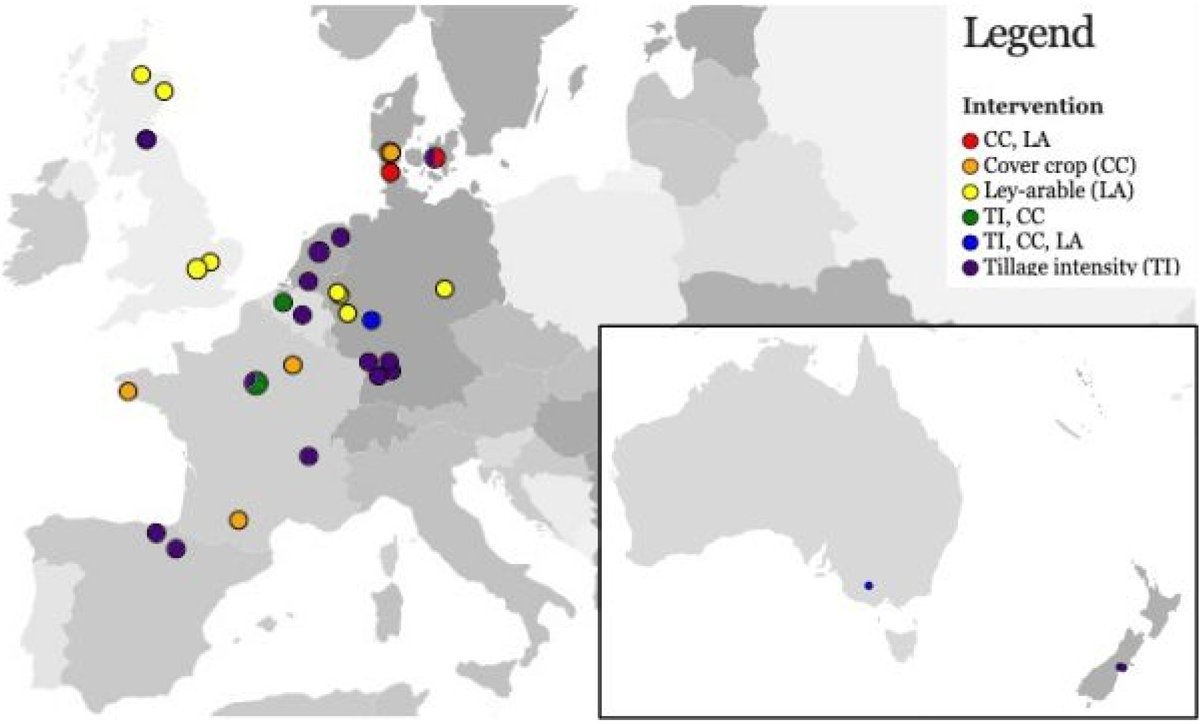

Figure 3

Systematic map. 40 relevant studies identified by systematic review process for inclusion in meta-analysis, created using the Thalloo framework 55. Position of pie charts reflects study locations (degrees decimal coordinates), size of pie charts is proportional to the number of studies in that region (or the site when zoomed in online), and the colour of the chart segments shows the number of studies of each intervention (see legend). Inset shows southern Hemisphere studies. An interactive version of this evidence map with the accompanying study database is available online at https://oxlel.github.io/evidencemaps/oceanic_climates/

Supplementary Files

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