Regenerative Agriculture practices and their influence on soil organic carbon and farm productivity in temperate regions

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Abstract

Global food production is currently contributing to numerous environmental challenges including anthropogenic climate change, biodiversity loss and widespread declines in soil health. Regenerative Agriculture (RA) is an emerging paradigm which proposes that restoring soil health, by adopting a suite of management practices that align with so-called ‘regenerative’ principles, will not only improve agricultural productivity but also contribute to climate change mitigation through increased soil organic carbon (SOC). Despite a plethora of policies and suggested practices emerging over the past decade to support the introduction of RA across the world, there is still remarkably little scientific evidence to quantify potential improvements in soil organic carbon or agricultural productivity as a result of adopting ‘holistic’ RA systems. This represents a large knowledge gap that I set out to address in my DPhil thesis using currently available evidence for individual management practices.

Research for my thesis was divided into four parts. First, I used gold-standard systematic review methods to collate the state of current knowledge and assemble datasets from published studies of management practices forming part of a RA approach. My study area was temperate oceanic regions and I examined papers that considered the following RA approaches: reduced tillage intensity, cover cropping and ley-arable rotations in arable systems, and rotational grazing, multi-species or herbal leys, and agroforestry in pasture systems. Second, using the datasets obtained from these published studies, I conducted Bayesian meta-analyses of the impact of these practices on SOC and agricultural productivity (crop yields, herbage

production, livestock growth). I found that adoption of rotational grazing and herbal leys can increase herbage dry matter production and livestock growth rates in pasture systems, but there is currently insufficient evidence to determine their impact on SOC. Conversely, my results identified clear potential for RA practices in arable systems to increase SOC but no evidence of a SOC-yield win-win. Third, using this finding I simulated adoption of these arable RA practices across Great Britain using the soil carbon model RothC, and found that in the UK there is the potential to mitigate 16-27% of current agricultural emissions through soil carbon sequestration. Finally, I conducted semi-structured interviews with industry representatives and livestock farmers in England to further understand advantages and disadvantages of implementing rotational grazing, herbal leys, ley-arable rotations and trees on farms. This final part of my research highlighted potential constraints on the ability to realise the theoretical advantages demonstrated from my earlier analyses.

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List of abbreviations

CEH - Centre for Ecology & Hydrology (UK)

CG – continuous grazing

CH_4 - methane

CI – Credible Intervals

CO_2 – carbon dioxide

CT – condensed tannins

DLWG – daily liveweight gain

DM – dry matter

FEC – faecal egg count

GB – Great Britain

GHG – greenhouse gas

GHGE – greenhouse gas emissions

HL – herbal leys

LU – livestock unit

$MtCO_2$ – megatonnes of carbon dioxide

NGO – non-governmental organisation

N_2O – nitrous oxide

NT – no tillage

PEG – polyethylene glycol

PRI – plant residue input

RA – Regenerative Agriculture

RG – rotational grazing

RothC – Rothamsted carbon model (version 26.3)

RT – reduced tillage

SOC – soil organic carbon

SOM – soil organic matter

TRM – tillage rate modifier

UK – United Kingdom

USA – United States of America

WW2 – World War Two

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Figure 4.2. RothC soil carbon pool dynamics, initialised for 500 years using conventional tillage (CT) plant residue input (PRI) from dataset, followed by simulated reduction of tillage intensity using tillage rate modifier (TRM) from year 500 (dashed vertical line). All parameters are mean values from implementation of respective modelling framework. **(a)** No-till: CT PRI 2.68 t.ha^{-1}.month^{-1}, TRM 0.95, SOC_{500} 47.4 t.ha^{-1}, SOC_{1000} 49.8 t.ha^{-1}. **(b)** Reduced tillage: CT PRI 3.52 t.ha^{-1}.month^{-1}, TRM 0.93, SOC_{500} 60.2 t.ha^{-1}, SOC_{1000} 64.4 t.ha^{-1}. DPM: decomposable plant material, RPM: resistant plant material, BIO: microbial biomass, HUM: humified organic matter, IOM: inert organic matter. Figure after Sierra (2015)

Figure 5.1. Distribution of Great Britain arable soil organic carbon (SOC) stocks (t.ha^{-1}). Baseline (assumed current, using WISE30sec values) (Batjes, 2016) and following implementation of cover crops, ley-arable rotations and reduced tillage intensity after 30 years (i.e. around the year 2050) and once a new equilibrium is reached, to 30 cm depth. Violin plots show distribution of mean values from each 1 km^2 model run for in Great Britain. Two ley-arable systems are modelled: L1A2, one year ley-phase and two years arable cropping, and L4A2, four years ley-phase and two years arable cropping. Simulations for two ley-arable scenarios and two reduced tillage scenarios were run together, respectively, hence shared baselines.

Figure 5.2. Great Britain arable soil organic carbon (SOC) stocks ($t.ha^{-1}$) at 1 km^2 resolution. Colour indicates difference from baseline (0-30 cm), following implementation of cover crops, ley-arable rotations and reduced tillage intensity after 30 years and once a new equilibrium is reached. The two scenarios for ley-arable rotations are one year ley-phase and two years arable cropping (L1A2), and four years ley-phase and two years arable cropping (L4A2). 1 km^2 resolution for arable land in Great Britain identified using the CEH land cover map (Rowland et al., 2017). Scale bar in km.

Figure 6.1. Conceptual diagram of spectra of grazing management intensity and pasture sward diversity. Rotational grazing and herbal ley practices fall along the x and y axes, respectively. These interact particularly in the lower left and upper right quartiles, where continuous grazing pressure can reduce sward diversity by removing palatable or sensitive species, and mob grazing can increase the natural sward diversity through unselective grazing and periods of rest, respectively. Note that the management implemented by Regenerative Agriculture practitioners is often of a higher intensity on these axes compared to published studies of rotational grazing and herbal leys analysed here. Although not displayed, the positive or negative effects of these practices are likely to saturate or plateau with time.

Figure 6.2. Evidence map. 115 relevant studies identified by systematic review process for inclusion in meta-analysis, created using the Thalloo framework (Martin, 2018). 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/agricultural_productivity/

Figure 6.3. Productivity effects of rotational grazing. Conditional effects of **a**) rest period (proportion of grazing season) on herbage dry matter production (DM, $t.ha^{-1}$), and **b**) rest period (proportion of grazing season) and stocking density ($LU.ha^{-1}$) on sheep and cattle daily liveweight gain ($g.day^{-1}$). Error bars show 95% Credible Intervals.

Figure 6.4. Productivity effects of herbal leys. Conditional effects of **a**) sward average root depth (m) and legume abundance on herbage dry matter production (DM, $t.ha^{-1}$), and **b**) leaf nitrogen concentration per leaf dry mass ($mg.g^{-1}$) and (**c**) sward average root depth (m) on sheep daily liveweight gain ($g.day^{-1}$). Error bars show 95% Credible Intervals.

Figure 6.5. Sheep growth and internal parasite effects of leaf condensed tannins (CT). Conditional effects of **a**) interaction between leaf CT concentration per forage dry mass ($g.kg^{-1}$) and polyethylene glycol (PEG, inhibits tannins) treatment on sheep daily liveweight gain ($g.day^{-1}$), **b**) interaction between leaf nitrogen concentration per leaf dry mass ($mg.g^{-1}$) and leaf CT concentration per forage dry

mass (g.kg^{-1}) on sheep daily liveweight gain (g.day^{-1}), and **c**) interaction between leaf CT concentration per forage dry mass (g.kg^{-1}) and anthelmintic treatment (wormer) on sheep daily liveweight gain (g.day^{-1}). Error bars show 95% Credible Intervals.

Figure A2.1. The literature searching and screening process, with the number of records included and excluded at each stage. For articles excluded at the full text screening stage, the number excluded for each reason are also given. This flow chart follows the template of (Haddaway et al., 2017b). † RGHL search undertaken for a separate meta-analysis following similar systematic review methods of rotational grazing and herbal ley interventions in temperate oceanic regions (Jordon et al., under review).

Figure A2.2. Forest plots showing treatment results from studies of reduced tillage intensity identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**) cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text methods), these are presented in the confidence intervals. Tillage treatment categories are conventional tillage (CT), reduced tillage (RT) and no-till (NT). The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals for each tillage category from a tillage-only meta-analysis are also shown. Note that main analysis results presented in text were estimated using full dataset across all interventions (see Methods in main text for details).

Figure A2.3. Forest plots showing treatment results from studies of cover cropping identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**) cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text methods), these are presented in the confidence intervals. The proportion of years in the arable rotation that cover crops were present is given. The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals of cover crop presence in rotation for no years or all years (expressed as proportion) from a cover crop-only meta-analysis are also shown. Note that main analysis results presented in text were estimated using full dataset across all interventions (see Methods in main text for details).

Figure A2.4. Forest plots showing treatment results from studies of ley-arable systems identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**) cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text

methods), these are presented in the confidence intervals. The length of the ley phase within the arable rotation for each treatment is given in years. The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals for ley durations of 0 and 1 year from a ley-arable-only meta-analysis are also shown. Note that main analysis results presented in text were estimated using full dataset across all interventions (see Methods in main text for details).

Figure A2.5. 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% Predictive 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 A2.6. Effect sizes of practice predictor terms. Model effects from six meta-analytical models fitted to (**a**) soil organic carbon concentration ($g.100g^{-1}$) and (**b**) crop yield ($t.ha^{-1}$) data, with error bars showing 95% Credible Intervals, as presented in Table 3.2. EP: error present; EI: error imputed; EIBP: baseline present, error imputed; EIBI: baseline and error imputed; CA: critical appraisal sensitivity analysis; SD: study duration sensitivity analysis; see main text Methods for further details.

Figure A3.1. Baseline Great Britain arable soil organic carbon (SOC) stocks ($t.ha^{-1}$) at 1 km^2 resolution. Averaged across simulations for each intervention for 0-30 cm. Calculated from SOC concentration (g.100g-1) and bulk density data from the WISE30sec dataset (Batjes, 2016), for all GB arable land at 1 km^2 resolution identified through the CEH land cover map (Rowland et al., 2017). Scale bar in km.

Figure A3.2. Proportion of uncertainty in RothC model output for Great Britain simulation explained by input parameter variation. Estimated from 6,137,400 observations (61,374 1 km^2 pixels) from the cover crop simulation. Adjusted R^2 from linear model with (**a**) baseline Plant Residue Input, and (**b**) soil carbon stock after 30 years of intervention, as response variables, and specified input parameter distributions as explanatory variables.

Figure A3.3. Proportion of uncertainty in RothC model output for model calibration explained by input parameter variation. Estimated using 61 observations from 8 studies with cover crop treatments identified by Jordon et al. (under review), i.e. CA data (see Table 5.2 and Section 5.4.1 for details). Adjusted R^2 from linear model with (**a**) treatment baseline Plant Residue Input, and (**b**) treatment endline Plant Residue Input, as response variables, and specified input parameter distributions as explanatory variables.

Figure A4.1. The literature searching, reverse snowballing, and screening process, with the number of records included and excluded at each stage. For articles excluded at the full text screening stage, the number excluded for each reason are also given. This flow chart follows the template of (Haddaway et al., 2017b).

Figure A4.2. Conditional effects of leaf nitrogen concentration per leaf dry mass ($mg.g^{-1}$) on wool growth, measured by studies either in **a**] $mg.cm^{-2}.day^{-1}$, or **b**] $g.day^{-1}$. Error bars show 95% Credible Intervals. Results from EP analysis. Conditional effects show the model-fitted values for individual interventions when all other model predictors are at the reference category.

Figure A4.3. Conditional effects of forage species on sheep daily liveweight gain ($g.day^{-1}$). Results from AV analysis (Appendix 4.2.2), i.e. only treatments with monoculture (single species) forage included. Perennial ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiforum*), Cocksfoot (*Dactylis glomerata*), Timothy (*Phleum pratense*), Tall fescue (*Festuca arundinacea*), White clover (*Trifolium repens*) Red clover (*T. pratense*), Birdsfoot trefoil (*Lotus corniculatus*), Greater birdsfoot trefoil (*L. pedunculatus*), Lucerne (*Medicago sativa*), Chicory (*Cichorium intybus*), Plantain (*Plantago lanceolata*). Numbers in parentheses on x-axis labels indicate number of observations in dataset for each species. Error bars show 95% Credible Intervals.

Figure A5.1. Age of participants interviewed, to the nearest 10 years.

Figure A5.2. Enterprise types of farmers interviewed in Devon and Northumberland. The ‘Sheep’ and ‘Beef’ categories include both farming breeding females and buying in store animals for rearing or finishing. The ‘Other’ category comprised ponies, honey, alpacas and a small dairy cattle herd.

Figure A5.3. Information sources used by farmers interviewed. ‘Farming press’ included weekly magazines such as the *Farmers Weekly* and *Farmers Guardian*. ‘Peer to peer networks’ included paid membership organisations, with livestock marts and grazing groups also mentioned by some participants. ‘Social media’ included industry webinars in addition to mainstream platforms. ‘Consultants’ comprised paid farm advisors and land agents. ‘Sales merchants’ referred to livestock feed, fertiliser or seed salespeople. ‘Formal education’ refers to agricultural college or university degree courses. ‘Other’ comprised inputs from books and the levy board.

Chapter 1. Introduction

Global food production currently contributes to numerous environmental challenges, including climate change, biodiversity loss, declining soil health, freshwater scarcity and nutrient pollution (IPCC, 2019, IPBES, 2019, UNCCD, 2017, Clark et al., 2020, Willett et al., 2019, Springmann et al., 2018). This is in part because production has substantially increased in recent decades to meet rising demand from both rapid population growth and greater prosperity (Godfray et al., 2010), notwithstanding yields plateauing for certain crops and regions (Ray et al., 2012). These issues are particularly acute for ruminant livestock (Godfray et al., 2018, Gerber et al., 2013b). Alongside dietary changes (Willett et al., 2019, Springmann et al., 2018), a key component of mitigating these negative impacts will be through accelerating adoption of alternative agricultural management practices which offer some combination of reducing environmental harms or increasing delivery of co-benefits per unit of food produced.

Regenerative Agriculture (RA) is one of the emerging management paradigms which proposes to do this, by restoring degraded soils, contributing to climate change mitigation, and increasing agricultural productivity through the process of building soil organic matter (SOM) (Moyer et al., 2020, Burgess et al., 2019, Newton et al., 2020). Because of its perceived multiple benefits it has recently been defined as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services” (Schreefel et al., 2020). The constituent

management practices promoted under RA overlap with other existing paradigms which aim to sustainably improve productivity or restore soil health, such as organic farming, agroecology, conservation agriculture and sustainable intensification (Lampkin et al., 2015, TABLE, 2021, Lal, 2015, Godfray and Garnett, 2014). However, RA has gained traction where some other paradigms have not due to the readily understandable and intrinsically positive message of 'regeneration' in combination with the appealing promise of a triple win between soil, climate and production benefits (Moyer et al., 2020).

There are several constituent practices of RA that have been utilised for many decades if not centuries. For example, integrating agriculture with trees was historically common practice in England, with pollard trees at field edges used as leaf browse for livestock and stored as 'tree hay' (Rackham, 1986). Furthermore, integration of livestock in arable systems via temporary leys (ley-arable rotations) was proposed as a means to build fertility and restore structurally degraded soils in the late 1800s (Elliot, 1908), and farmland in the UK has transitioned repeatedly between arable cropping and grasslands over previous centuries, albeit often driven by external circumstances (Stubbings, 2002). Elliot (1908), for example, recounted a meeting of 400 Aberdeenshire farmers in the mid 1800s, who "declared that one of the three great causes of their difficulties was the exhaustion of the soil". The solution to declining fertility and loss of SOM in Britain proposed by Elliot, and others who built on his ideas during and following WW2, was to incorporate a ley phase (often a herbal ley) grazed by livestock into arable rotations, thus achieving

remarkable yields (for the time) on previously poor ground with little or no artificial fertilisers (Elliot, 1908, Henderson, 1943, Turner, 1951, Stapledon and Davies, 1948). In addition, rotational grazing through subdivision of pastures was being practiced in north-west Europe as early as the 18 century (Voisin, 1959), and seed mixes containing deep rooting herbs were developed in the Scottish borders in the late 1800s due to the recognised benefits of these in the sward (Elliot, 1908) and were subsequently further promoted (Turner, 1951).

It can be tempting to view RA as simply another re-packaging of the same suite of practices, which often have a much longer history of adoption in UK farming than many realise. However, a key aspect of RA is the adoption of a new management paradigm and decision-making framework, rather than simply simultaneously implementing a basket of already-existing practices. Pioneers of RA have suggested five key principles to improve soil health (Brown, 2018), aligned with the practices considered in my thesis in Table 1.1, along with a holistic and adaptive decision-making framework (Savory and Butterfield, 2016).

Table 1.1. The Five Principles of Soil Health proposed by Gabe Brown (Brown, 2018) and how these relate to the Regenerative Agriculture practices I consider in my DPhil

Principles of Soil Health	RA practice considered here
Limit mechanical, chemical and physical disturbance of the soil	Reduced tillage intensity
Maintain cover of plant residues on soil surface	Cover crops; ley-arable during ley phases
Promote diversity	Herbal leys; trees on farms and cover crops
Keep living roots in the soil	Cover crops; mob grazing; herbal leys (increasing rooting depth)
Integrate animals on the farm	Ley-arable; rotational grazing; herbal leys

As such, the appealing narrative associated with RA is rapidly gaining popularity among land managers, policy makers, NGOs and large corporations (Burgess et al., 2019, Giller et al., 2021, Newton et al., 2020). Practices promoted as part of regenerative approach have become more widely adopted temperate oceanic regions such as the UK in recent years. These include reducing tillage intensity in seedbed preparation for arable crops, growing over-winter cover crops between annual cash crops, integrating grass-based temporary leys into arable rotations, and adopting agroforestry, rotational grazing, and herbal leys in pasture systems. These individual management practices are also of increasing interest to policy makers seeking to boost farmland carbon stocks as part of national climate change mitigation strategies, such as the UK's target of net zero emissions by 2050 (Climate Change Committee, 2020), or more broadly enhance environmental outcomes such as via the recently reformed Common Agricultural Policy in the European Union or the new Environmental Land Management schemes in England (Defra, 2021b, Defra, 2021a). Furthermore, these RA practices may also offer a route to improving the environmental sustainability of ruminant livestock, through a combination of:

i. Mitigating negative environmental impacts of livestock – including greenhouse gas emissions, increased flood hazard, and reduced water and air quality (Gerber et al., 2013a, Bilotta et al., 2007, Marshall et al., 2014) – by integrating trees into production systems (i.e. agroforestry),
ii. Using livestock to deliver benefits in arable systems through building fertility and reducing arable weed burdens (i.e. ley-arable rotations) (Lemaire et al.,

2015, Schut et al., 2021), thus reducing or eliminating inorganic fertiliser and herbicide applications, and

iii. Improving productivity of the livestock (e.g. through rotational grazing or herbal leys) thus reducing environmental impacts such as greenhouse gas emissions per unit of produce (Herrero et al., 2016, Hristov et al., 2013).

However, there are still large scientific knowledge gaps relating to the full environmental and agronomic benefits of RA. One of particular importance is understanding whether transitioning to RA systems would deliver a win-win between enhancing soil organic carbon (SOC) for climate change mitigation and improving farm productivity.

The overarching aim of my DPhil research is to address this knowledge gap and to determine the effectiveness of RA practices in temperate oceanic regions as a means to simultaneously increase farmland SOC stocks and agricultural productivity. Although I primarily consider the policy implications of this from a UK perspective, I synthesise evidence across temperate oceanic regions in order to draw from the broadest possible evidence base generalisable to my context of interest. To achieve this, I used quantitative and qualitative approaches to address three interlinked objectives:

1. Synthesis of the currently available published evidence regarding the impact of selected RA practices on SOC and agricultural productivity

2. Determination of the role of different RA practices in increasing SOC as part of territorial climate change mitigation efforts
3. Assessment of the likely appeal of RA practices to land managers

My thesis describes the outcome of this research and is arranged into seven further chapters as follows:

Chapter 2 sets out a systemic evidence map in which I synthesise published literature regarding the impacts of temperate agroforestry on sheep and cattle productivity, environmental impacts and farm economic viability. In this, I evaluate the synergies and trade-offs between environmental, productivity and economic indicators from integrating trees onto livestock farms.

Chapter 3 presents the results of a further systematic literature review. I extract data from experimental studies in order to conduct a Bayesian meta-analysis of the impact of three RA practices applicable to arable systems (reduced tillage intensity, cover cropping and ley-arable rotations) on SOC and crop yield.

Chapter 4 presents a novel approach which I develop to represent the impact of reduced tillage intensity on SOC within the process-based soil carbon model RothC. This uses data extracted as part of the systematic review in Chapter 3.

Chapter 5 combines soil carbon data assembled in Chapter 3 and the modelling approach developed in Chapter 4, which I use to estimate the total change in soil carbon stocks if these three arable RA practices were adopted at a country-scale for Great Britain (England, Scotland and Wales).

Chapter 6 considers additional RA practices, in this case applicable to pasture systems (rotational grazing and herbal leys). I make use of quantitative predictors in Bayesian hierarchical models to investigate the effectiveness of these practices for increasing herbage growth and livestock growth rates.

Chapter 7 grounds the theoretical estimates from previous chapters by evaluating the adoption of RA management likely achievable in practice by farmers. I conduct semi-structured interviews with farmers and industry representatives in England to identify advantages, disadvantages, and possible reasons for non-adoption of four practices relevant to beef cattle and sheep farming: rotational grazing and herbal leys from Chapter 6, ley-arable from Chapter 3 and trees on farms from Chapter 2.

Chapter 8 concludes my thesis by discussing the implications of my findings for efforts to further promote RA practices in temperate oceanic regions, and their potential role in the UK in improving ruminant livestock environmental sustainability.

The **Appendices** contain supplementary material to support Chapters 2-7.

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Chapter 2. Implications of temperate agroforestry on sheep and cattle productivity, environmental impacts and enterprise economics. A systematic evidence map

2.1. Summary

This chapter presents the results of my synthesis of 289 published studies examining the environmental, economic and production benefits associated with temperate agroforestry. Using systematic evidence mapping methods, I identified an evidence base which demonstrates that temperate agroforestry can deliver environmental and economic benefits compared to pasture without trees. In contrast, I found that livestock productivity indicators have not received sufficient attention, in many temperate agroforestry systems, to draw firm conclusions on their benefits or otherwise. The output of my systematic map contributed important knowledge to addressing the first aim of my thesis namely understanding the relationship between soil carbon and agricultural production following adoption of Regenerative Agriculture practices. This chapter identified studies which have demonstrated that temperate agroforestry can increase carbon stocks both in woody biomass and soils relative to pasture without trees. Furthermore, these studies indicate that total productivity (tree plus understory) is increased in integrated systems, although there often appears to be a trade-off with forage production in proximity to trees. As such, there is some evidence to suggest that agroforestry may deliver a carbon and production win-win as part of Regenerative Agriculture.

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Implications of temperate agroforestry on sheep and cattle productivity, environmental impacts and enterprise economics. A systematic evidence map

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2.2. Abstract

Background and Objectives: The environmental impacts of ruminant livestock farming need to be mitigated to improve the sustainability of food production. These negative impacts have been compounded by the increased spatial and cultural separation of farming and forestry across multiple temperate landscapes and contexts over recent centuries, and could at least in part be alleviated by re-integration of livestock and trees via agroforestry systems. Such integration also has the potential to benefit the productivity and economics of livestock farming. However, the delivery of hoped-for benefits is highly likely to depend on context, which will necessitate the consideration of local synergies and trade-offs. Evaluating the extensive body of research on the synergies and trade-offs between agroforestry and environmental, productivity and economic indicators would provide a resource to support context-specific decision making by land managers. Here, we present a systematic evidence map of academic and grey literature to

address the question “What are the impacts of temperate agroforestry systems on sheep and cattle productivity, environmental impacts and farm economic viability?”. *Materials and Methods:* We followed good practice guidance from the Collaboration for Environmental Evidence to find and select relevant studies to create an interactive systematic map. *Results:* We identified 289 relevant studies from 22 countries across temperate regions of North and South America, Australasia, and Europe. Our preliminary synthesis indicates that there is an emerging evidence base to demonstrate temperate agroforestry can deliver environmental and economic benefits compared with pasture without trees. However, to date measures of livestock productivity (particularly weather-related mortality and heat- and cold-stress) have received insufficient attention in many temperate agroforestry systems. *Conclusions:* The evidence base assembled through this work provides a freely accessible resource applicable across temperate regions to support context-specific decision making.

2.3. Introduction

Management of agricultural land has an important role to play in addressing the twin challenges of climate change and biodiversity loss (IPCC, 2019, IPBES, 2019). In particular, the environmental impacts of ruminant livestock farming need to be mitigated to improve the sustainability of food production, amid rising demand for animal-sourced foods driven by human population growth and increasing affluence (Springmann et al., 2018, Godfray et al., 2018). Currently, domestic

sheep and cattle are a significant source of anthropogenic greenhouse gas emissions (GHGEs) (Gerber et al., 2013b), and can contribute to air pollution (Tang et al., 2018), increased flood hazard (Graves et al., 2015), reduced water quality and enhanced soil erosion (Bilotta et al., 2007). These negative environmental impacts have, in temperate regions, been compounded by the increased spatial and cultural separation of farming and forestry across multiple landscapes and contexts over recent centuries, along with more recent widespread removal of trees and other woody landscape elements as part of agricultural intensification (Mead, 1995, Biasi et al., 2016, Brown and Schulte, 2011, Vera, 2000). Re-integration of trees and farming systems, via a diverse suite of practices collectively termed agroforestry (Gordon et al., 2018), has the potential to at least in part alleviate these environmental harms (Table 2.1, and citations therein).

Table 2.1. Selected environmental impacts of ruminant livestock production, used as outcomes in the systematic map, and how trees could potentially mitigate these impacts. Natural capital assets and societal benefits affected (NCC, 2017) are also indicated.

Environmental indicators	Ruminant action	Details of negative environmental impact caused by ruminants	Ecosystem services that can be provided by trees to mitigate this impact	Natural capital assets affected	Societal outcome affected
Greenhouse gas emissions & carbon	Eructation + urination & defecation (i.e. manure production)	Emissions: Methane from eructation & manure Nitrous oxide from manure & fertiliser applications Carbon dioxide from machinery & embedded in animal feed production (Gerber et al., 2013b)	Carbon sequestration in above- and below-ground tree biomass and soil (Doran-Browne et al., 2016, Briner et al., 2012)	Air & soil	Stable climate
Air quality		Emissions of air pollutants, e.g. ammonia (Tang et al., 2018)	Particulate capture by tree leaves (Bealey et al., 2016)	Air	Clean air
Water quality		Nutrient loss in run-off from fields into groundwater and watercourses (Bilotta et al., 2007)	Nutrient capture by tree roots (Udawatta et al., 2010)	Water	Clean water
Water quantity	Trampling & grazing pressure	Reduced water infiltration caused by soil compaction leading to increased water runoff from fields (Heathwaite et al., 1990)	Increased water infiltration into soil facilitated by tree roots (Carroll et al., 2004, Marshall et al., 2014) and increased transpiration rate of trees (Bosch and Hewlett, 1982)	Soil & water	Flood hazard protection
Soil erosion		Soil erosion (Bilotta et al., 2007)	Slope stabilisation and sediment capture by tree roots (McIvor et al., 2008)		Sustained basis for food production

Simultaneously, increasing tree cover on a global scale is attracting international policy and academic attention as a so-called nature-based solution to contribute to climate change mitigation and biodiversity protection (Griscom et al., 2017, Bastin et al., 2019, Strassburg et al., 2020). Managed grasslands grazed by domestic ruminants are often identified as suitable locations for afforestation and some simplistically argue that ruminant livestock production should be wholly replaced by forest restoration e.g. (O'Neill et al., 2020). However, integrating instead of simply replacing livestock with trees, i.e. agroforestry, is widely recognised as having a role to play in increasing tree cover for environmental reasons whilst enabling continued food production (IPCC, 2019, CCC, 2018, Smith et al., 2008, Griscom et al., 2017). Furthermore, temperate agroforestry can improve farm financial viability (McAdam et al., 1999, Hardaker, 2018) and deliver livestock productivity and welfare benefits such as increased pasture production (Bird, 1998) and reduced livestock heat and cold stress (Armstrong, 1994, Van Laer et al., 2015, Bird et al., 1984).

Although agroforestry systems as a concept were developed in the tropics, there is now a substantial body of evidence from temperate regions on the environmental, productivity and economic implications of integrating trees and food production (Gordon et al., 2018). Previous temperate evidence syntheses have focused on a limited geographic area e.g. (Fagerholm et al., 2016, Torralba et al., 2016, Kay et al., 2018) or single productivity or environmental indicators e.g. (Hawke, 1991,

Benavides et al., 2009, Lorenz and Lal, 2014, Carrick et al., 2018). However, there is yet to be a systematic compilation of agroforestry evidence across environmental, productivity and economic indicators and temperate regions. This is important because although policy makers may promote agroforestry for environmental reasons, enterprise productivity and economic factors are likely to be key in stimulating land manager uptake (Hardaker, 2018). As such, it is key to understand potential synergies and trade-offs in the delivery of hoped-for benefits from agroforestry and how these depend on context, including climatic and site conditions, livestock and tree species, relevant commodity prices and method of integration.

Here, we systematically map the evidence of the impacts of integrating trees (including shrubs and perennial bioenergy crops, i.e. woody vegetation) into temperate ruminant production systems. Systematic map methods provide a rigorous, objective and transparent means of creating a searchable database of relevant academic and grey literature (James et al., 2016), whilst providing an opportunity to characterise the evidence base and highlight knowledge gaps. Our systematic map addressed the question "What are the impacts of temperate agroforestry systems on sheep and cattle productivity, environmental impacts and farm economic viability?". The question was structured following the Population, Intervention, Comparator, Outcome, Location (PICOL) format (Table 2.2). We focused on studies that had addressed the following environmental impacts:

GHGEs, reduced water and air quality, increased flood hazard and enhanced soil erosion (Table 2.1). A key aim was to establish the published evidence base demonstrating the potential of agroforestry to mitigate these environmental impacts of ruminant production. We also aimed to capture studies that had demonstrated the delivery of these ecosystem services by the tree component of agroforestry systems without specifically considering any mitigation of the livestock component. The database of studies assembled provides a resource to support context-specific decision making by land managers, academics and policy makers across temperate regions, whilst identifying future field-based research priorities and enabling further quantitative meta-analysis.

Table 2.2. Question breakdown of systematic evidence map, following the PICOL format.

PICOL element	Question element	Details
Population	Sheep	*Ovis aries*
	Beef and dairy cattle	*Bos taurus*
Intervention	Agroforestry	Systems with woody perennials, pasture and livestock. This includes silvopasture, shelterbelts, windbreaks, riparian strips, hedges, Dehesa, Montado, wood pasture, forest grazing, orchards, woody biofuel and farm woodlands
Comparator	Livestock farming systems with pasture but no trees/shrubs OR forestry systems with trees but no livestock	
Outcome	Productivity	Understory/pasture productivity
		Livestock mortality
		Livestock growth rate
		Livestock heat stress
		Livestock cold stress
	Environmental indicators	Greenhouse gas emissions or carbon stocks/sequestration
		Water quantity

		Water quality
		Air quality
		Soil erosion
	Enterprise economics	Financial implications for land manager
Location	Temperate systems	Temperate regions of North and South America, Europe and Australasia

2.4. Materials and Methods

We followed Collaboration for Environmental Evidence (CEE) guidelines (CEE, 2018) and methodology therein to create our systematic evidence map, and followed the Reporting standards for Systematic Evidence Syntheses (ROSES) forms to describe our outcomes (Haddaway et al., 2017). Agroforestry networks in English-speaking countries with temperate agroforestry systems, identified from Gordon et al. (2018), were contacted for feedback on the suitability of the review questions. A request was also made to these stakeholders for submission of any relevant grey literature that they were aware of and might not be picked up through bibliographic databases or citation indexes (Appendix 1.1.2).

Details of the search strategy used are given in Table 2.3 and Appendix 1.1. The first search of bibliographic databases took place on 27 September 2019. The comprehensiveness of the search was estimated using a test list of 23 articles (Appendix 1.1.4). Nine of the 23 test articles were missed by the initial search, so additional search terms were added until all test articles were recovered during the search. The definitive search with results taken forward for screening took place on

2 October 2019. All databases were searched for “All years”, i.e. there was no restriction on publication date during the search or screening.

Table 2.3. Methods for each component of the systematic literature search strategy

Search string	For the full search string used, see Appendix 1.1.1. The search string was structured by PICOL elements (Table 2.2). Terms are joined by 'OR' Boolean operators within PICOL elements and 'AND' operators between elements. The same search string was used across all bibliographic databases and citation indexes
Languages – bibliographic databases	English only
Languages – grey literature	English only
Bibliographic databases & citation indexes	Web of Science (databases searched listed in Appendix 1.1.1.1), CAB Abstracts, Scopus
Organisational websites	Five stakeholder organisations were contacted by email (Appendix 1.1.2) and 15 organisational websites were searched (Appendix 1.1.3)
Estimating the comprehensiveness of the search	A test list of 23 articles was compiled (Appendix 1.1.4) from reviews read at the initial scoping stage (Lampkin et al., 2015, Raskin and Osburn, 2019, Gordon et al., 2018)

Only studies that exactly met our PICOL elements (Table 2.2) were included in the evidence map. For details of the inclusion/exclusion criteria applied to records during screening, see Appendix 1.2.1. All title and abstract screening was carried out in Endnote X9.3. It was not possible to check consistency of screening decisions at these stages due to only one reviewer screening. However, a conservative screening approach was adopted whereby articles were only excluded if deemed highly likely to be irrelevant. During title screening, any additional duplicates that hadn't been detected by Endnote's automated duplicate finder (e.g. due to author or title names in being in different formats) were excluded. Records with no title were screened by abstract and included/excluded

accordingly. During abstract screening, 799 records with no abstract were identified (Fig 2.1). These were later rescreened based on title and separated into two groups: higher priority (61 records most likely to be relevant at full text) and lower priority (738 records unlikely to be relevant at full text). Full texts for the 61 higher priority records were searched for and coded accordingly at the full text screening and coding stage.

Article full texts were screened for relevance in the order Location, Population, Intervention, Comparator, Outcome, such that the exclusion reason given is the first of these criteria that the article didn’t meet. Article full texts were initially screened in batches of 10 by two reviewers, with a Cohen’s unweighted kappa calculated for each batch to provide a measure of inclusion/exclusion consistency between reviewers (Cohen, 1960). The initial kappa score was 0.28. Discrepancies were discussed and resolved after each batch, until the kappa score reached 0.81 - exceeding the recommended threshold of 0.60 (CEE, 2018) - at which point the reviewers screened and coded independently. Double screening was conducted on 100 articles (out of a total of 1,352 retrieved at full text) to check for consistency in this manner. All data coding was undertaken in Microsoft Excel, using drop-down options to ensure categorical and consistent data entry. Discrepancies in coding decisions were discussed and resolved in a similar manner to screening discrepancies. For a full list of article meta-data and variables that were coded, see Table A1.2.

No critical appraisal of study internal or external validity was undertaken. This is consistent with CEE guidelines as the purpose of the map is to document the evidence base rather than measure effect sizes through meta-analysis. However, it is important to note that studies were rejected where elements of our inclusion criteria were missing, so this evidence map has a high degree of filtering in place that ensures that only studies with clearly reported study designs and results were included.

All figures were plotted in R using the *ggplot2* package. The interactive evidence map of the all relevant studies was created using the Thalloo mapping framework (Martin, 2018). We used these to assess knowledge gaps and clusters in the evidence and observe any trends in study findings. We have been careful not to over-interpret numbers of ‘recorded outcomes’ in the evidence map, given that no statistical analyses were undertaken. Our analyses were limited to answering the simple question “is there any evidence of an effect”, not what is the size of the effect (Bushman and Wang, 2009).

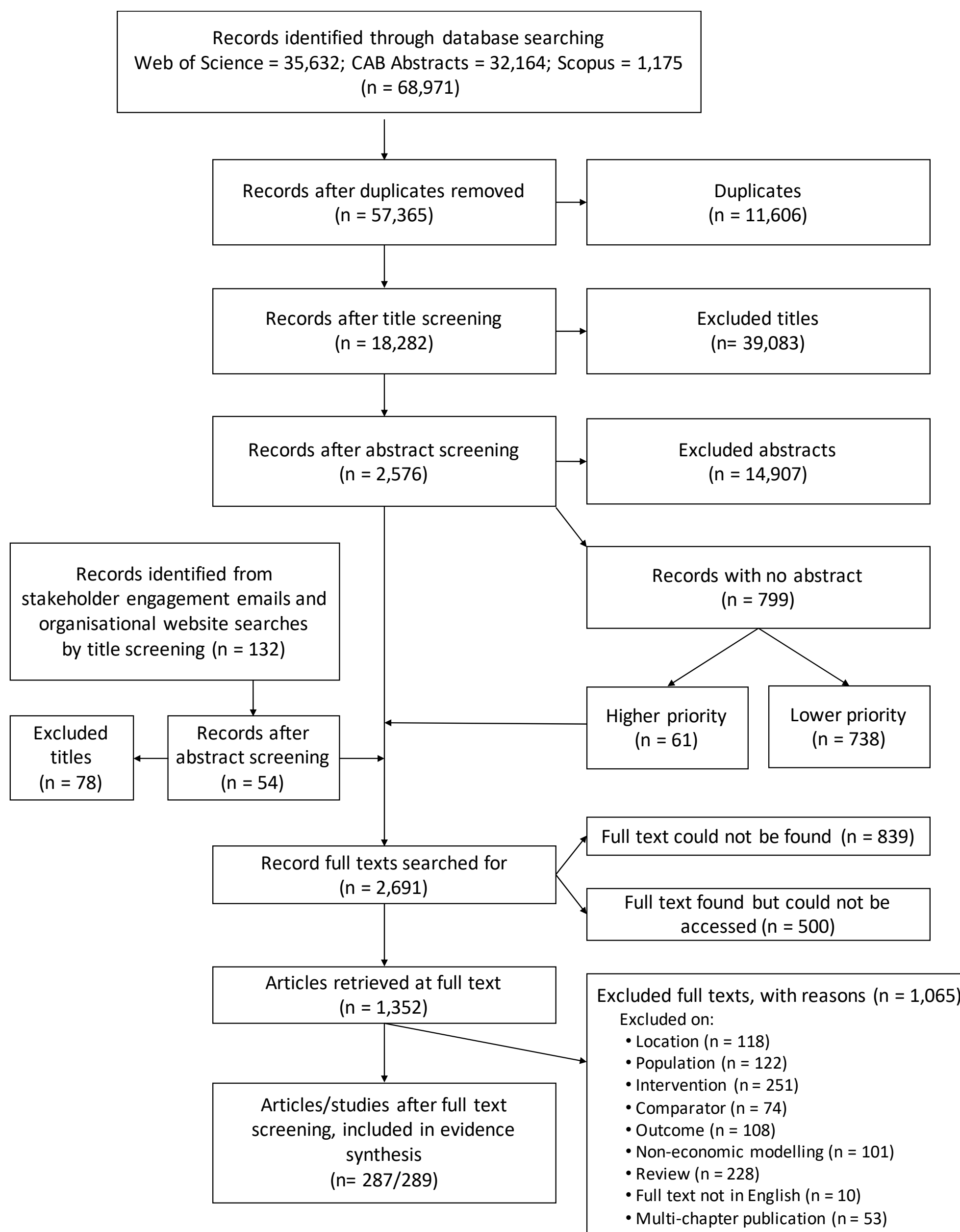

Figure 2.1. The literature searching and screening process, with the number of records included and excluded at each stage. For articles excluded at the full text screening stage, the number excluded for each reason are also given. Two full-text-relevant articles were separated into two studies each, hence the close similarity between the number of articles/studies included in the evidence synthesis. This flow chart follows the template of Haddaway NR (2017).

2.5. Results and Discussion

*2.5.1. **Search** results*

From 68,971 records identified through searches of bibliographic databases, and a further 132 identified from organisational websites and stakeholder engagement, 287 articles (289 studies) were screened as relevant at full-text screening for inclusion in this evidence database (Fig 2.1). Details of the 2,692 articles that full texts were searched for are recorded in the Supplementary Table available with the online version of the published article.

Separate evidence maps were plotted for productivity, GHGEs/carbon and economics showing recorded outcomes (links to online versions provided in the relevant results sections below). These interactive maps and accompanying databases can be filtered and queried by publication year, country (location), livestock type (population), agroforestry system (intervention), comparator, and productivity, environmental or economic outcomes to provide the searcher with the desired literature (see the help file in online map descriptor for further details).

2.5.2. Study spatial and temporal distribution

We identified relevant studies in 22 countries across temperate regions of Europe, North and South America and Australasia (Table 2.4, Fig 2.2). The total number of studies considering cattle and sheep are approximately equal (90 and 89

respectively), although this proportion fluctuates between countries (Table 2.4). The publication year of relevant studies indicates an exponential increase in the number of publications, in line with a broader trend in the scientific literature (Petrokofsky et al., 2013). The earliest relevant record was published in 1942, but 90% of relevant studies were published in or after 1990.

The temperate agroforestry evidence base is predominantly from a small number of countries; 76% of studies in our map are from the USA, New Zealand, Australia, the UK or Spain (Table 2.4). Although further research in relatively underrepresented temperate countries (e.g. much of Europe) would be useful in providing locally relevant and context-specific evidence, agroforestry trials are expensive to establish and take a long time to mature. Therefore, it could be more effective to investigate how relevant and applicable evidence from well-studied countries such as the USA or New Zealand is to contexts and countries with much less existing research. This could complement investment in new trials by informing dissemination programmes in the short to medium term.

Table 2.4. Number of studies included in evidence map separated by country of study (Location) and livestock type (Population), ordered in descending frequency.

Country of study	Livestock type					
	Cattle	Sheep	Mixture of sheep and cattle	Unclear from study	Pasture without livestock†	Total
USA	41	14	1	5	10	**71**
New Zealand	4	10	23	7	8	**52**
Australia	4	23	7	8	4	**46**
UK	6	17	3	5	-	**31**
Spain	1	7	3	3	7	**21**
Canada	8	1	-	2	-	**11**
Portugal	2	5	-	2	1	**10**
Chile	6	3	-	-	-	**9**
Argentina	5	-	-	2	1	**8**
Italy	2	2	2	3	-	**9**
France	1	3	-	-	-	**4**
Greece	-	2	-	-	1	**3**
Belgium	3	-	-	-	-	**3**
Netherlands	1	-	-	1	-	**2**
Austria	2	-	-	-	-	**2**
Finland	1	1	-	-	-	**2**
Switzerland	1	-	-	-	-	**1**
Hungary	-	-	-	-	1	**1**
Poland	1	-	-	-	-	**1**
Romania	-	1	-	-	-	**1**
Sweden	1	-	-	-	-	**1**
Total	**90**	**89**	**39**	**38**	**33**	**289**

† Studies of pasture without livestock were searched for and included (Appendices 1.1 & 1.2.1) in order to find studies that quantify pasture production under agroforestry without referring specifically to livestock types.

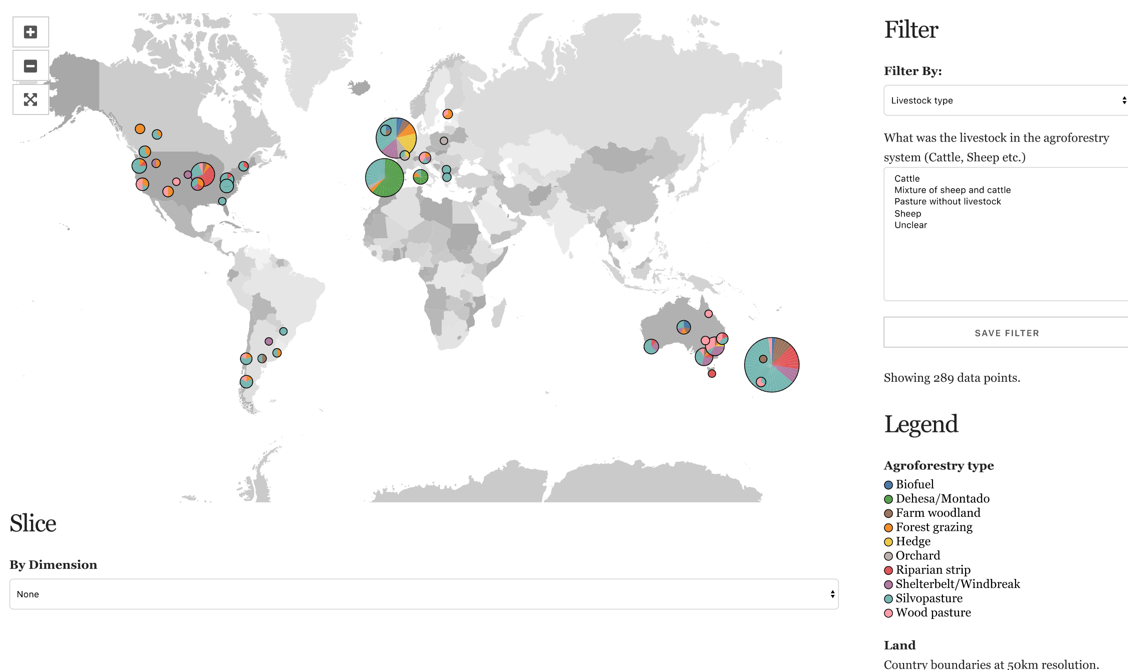

Figure 2.2. Map of 289 relevant studies included in evidence synthesis. Position of pie charts reflects study locations (degrees decimal coordinates), size of pie charts is proportional to the number of studies in that region (or site when zoomed in online), and colour of chart segments shows the number of studies of each agroforestry type (see legend). An interactive version of this evidence map with accompanying database is available online at https://oxlel.github.io/evidencemaps/agroforestry_main/

2.5.3. Outcomes - Productivity

We identified 155 studies that recorded productivity measures in a livestock agroforestry system. Measures of 'productivity' in these studies included pasture growth rates or herbage yield (i.e. tree understory or pasture production) and livestock growth rates, milk yield, mortality and heat- or cold-stress. Twenty-four studies included both a pasture-related measure and a livestock-related measure, so were included as separate records, resulting in 179 records in the evidence

database, mapped with recorded outcomes at https://oxlel.github.io/evidencemaps/agroforestry_productivity/

Most records (58%) compared the impacts of agroforestry with pasture without trees. Of 179 records, 51% measured pasture production, 24% measured livestock growth, 17% measured total pasture plus tree production, with the other livestock measures (mortality, heat and cold stress, and milk yield) comprising the remainder. Pasture production, livestock growth, and total pasture plus tree production were most commonly measured in silvopasture (60%) and forest grazing (13%) systems, whereas most (64%) measures of livestock mortality, heat and cold stress and milk yield were from shelterbelt or windbreak systems.

Although there is a substantial evidence base on the impact of agroforestry systems on pasture production and livestock growth rates, other measures of livestock productivity have received much less attention. This is problematic because one of the key incentives for temperate livestock farmers to uptake agroforestry is considered to be the benefits of shade or shelter on livestock heat and cold stress and mortality (WoodlandTrust and NSA, 2014). While all bar one studies of livestock mortality, milk yield and heat and cold stress identified by this map found that agroforestry had a positive effect, this is from a total of only 14 studies, which includes grey literature case studies as well as empirical peer-review scientific literature. This finding must therefore be treated with caution until further studies emerge. This number of studies is also too small to confidently identify the factors

(e.g. climatic conditions, tree species, tree planting density etc.) that underpin the apparent variation in magnitude and direction of effects that is seen between studies.

In terms of negative impacts, 53% of studies on pasture production found that agroforestry either had an outright negative effect on production or that it showed an incremental decrease with increased tree density (stems per ha), cover (% canopy) or proximity to pasture measured. This finding is in line with conclusions of previous reviews on this topic (Hawke, 1991, Benavides et al., 2009). However, only 20% of livestock growth studies found an outright negative effect. This disparity confirms that pasture production is likely not the only factor influencing livestock growth, and indicates the importance of other factors like pasture quality (e.g. crude protein content (Peri et al., 2007)) and the effects of tree shade on reducing livestock heat and cold stress. Although some studies also measured pasture quality, we did not include this in our evidence mapping. Further empirical work is needed to determine the factors that drive differences in livestock growth between agroforestry systems and pasture without trees, in order to establish the conditions under which other benefits of tree presence compensate for reduced pasture production resulting in an overall positive effect on livestock growth rates.

2.5.4. Outcomes – Environmental indicators

2.5.4.1 Greenhouse gas emissions & carbon stocks

We identified 77 studies that quantified the impact of agroforestry with livestock on GHGEs or carbon stocks. Three of these studies included measures of two different

carbon stocks in the agroforestry system, so were included as separate records, resulting in 80 records in the evidence database. These are mapped with recorded outcomes at https://oxlel.github.io/evidencemaps/agroforestry_carbon/

Approximately 75% of these records quantified impacts on soil carbon (soil organic carbon, soil organic matter or total soil carbon), of which 42% were in silvopasture systems and 27% in *dehesa* or *montado* systems. When compared to pasture without trees, soil carbon was often found to be higher in agroforestry systems (Fig 2.4a, also explore map link directly above). This accords with the mechanisms reviewed by Lorenz and Lal (2014) which include the potential of the tree component of agroforestry systems to increase inputs of belowground carbon through root litter and exudates, and improve productivity and therefore soil carbon sequestration through nutrient and water uplift from deeper soils inaccessible to herbage. There is also some evidence that implementing silvopastoral systems can result in higher total carbon stocks (soil plus tree biomass) than if the equivalent number of trees was planted as woodland separate to pasture (Upson et al., 2016, Beckert et al., 2016b, Fornara et al., 2018).

Only six studies explicitly examined the potential of agroforestry to offset or mitigate the GHGEs associated with ruminant livestock (Petersen et al., 2003, Doran-Browne et al., 2016, Doran-Browne et al., 2018, Dube et al., 2011, Briner et al., 2012, Ripamonti and den Herder, 2019). All demonstrated that agroforestry systems have potential to mitigate at least some of the emissions associated with the livestock

component through carbon sequestration in the tree component. However, meta-analyses and modelling of carbon sequestration of different agroforestry systems would need to be coupled with context-specific lifecycle assessments of livestock production under each of these systems in order to demonstrate an empirical baseline in which agroforestry offers an effective and/or complete livestock GHGE mitigation strategy.

Although there are several viable technical options to mitigate ruminant-associated emissions (Gerber et al., 2013a, Hristov et al., 2013, Herrero et al., 2016), using agroforestry practices to offset remaining emissions via compensatory carbon sequestration in woody biomass and soil is not without challenges or controversy. For example, the carbon sequestration potential of agroforestry systems is likely to saturate over time (Lorenz and Lal, 2014), through a combination of the soil carbon pool reaching a new equilibrium and tree growth slowing or stopping upon maturity. To achieve continuous carbon sequestration, livestock farmers would need to manage trees in a harvesting and restocking cycle, with a guarantee that the end-use of the timber harvested was not going to result in the release of the stored carbon (e.g. by use in construction rather than bioenergy). Furthermore, methane from eructation (belching) and manure forms the majority of emissions associated with temperate ruminant production (Gerber et al., 2013b). Because this is a short-lived gas that reaches an equilibrium concentration in the atmosphere under stable emissions, this has been demonstrated to be equivalent in terms of warming to net zero emissions of carbon dioxide (Lynch et al., 2020). Although this has led some to

question whether stable methane emissions need to be offset at all, others contend that methane offers a “particularly attractive target gas for short-term climate change mitigation” (Smith and Balmford, 2020).

In this systematic evidence map we focused on carbon sequestration, as the most direct mechanism by which agroforestry systems could mitigate the climate change impacts of GHGEs associated with ruminant production, and did not consider non-CO_2 greenhouse gases. However, nitrous oxide emissions are a key environmental impact associated with agricultural generally (predominantly via synthetic fertiliser applications) (Reay et al., 2012), and ruminant livestock specifically (via manure production and management), which receives substantial policy attention. It is clear that inclusion of trees in agricultural systems via agroforestry can affect nitrous oxide emissions (Tully and Ryals, 2017, Baah-Acheamfour et al., 2017, Shvaleva et al., 2015, Franzluebbers et al., 2017) and although a recent meta-analysis found no clear overall direction of effect (Kim et al., 2016), this should be included in future evidence syntheses.

2.5.4.2 Water quantity

Twenty-two studies quantified the effect of an agroforestry intervention on water quantity (by measuring water runoff, infiltration or hydraulic conductivity) across six of the 22 countries covered by this systematic map. Of these, approximately half (55%) found agroforestry to have a significant positive effect including lower runoff and higher soil infiltration capacity.

Although planting trees is widely held to be an effective strategy for flood hazard reduction, this is increasingly recognised as a simplistic view (Calder and Aylward, 2006), with a recent meta-analysis finding tree planting to have a modest but highly variable impact on channel discharge (Carrick et al., 2018). Moving from the catchment to field scale, research on the potential of trees planted in agroforestry systems to mitigate any increase in surface runoff caused by livestock trampling indicates that the presence/absence of livestock is likely to be as, if not more, important than the presence/absence of trees (Marshall et al., 2014, Lunka and Patil, 2016, Chandler et al., 2018). This suggests that linear field-edge agroforestry systems such as riparian strips and shelterbelts where livestock are excluded hold more potential for mitigating any livestock-induced runoff from pasture than systems with livestock grazing underneath trees such as silvopasture.

2.5.4.3. Water quality

Twenty-seven studies quantified the effect of an agroforestry intervention on water quality, through measuring water sediment or nutrient concentrations. Riparian strips were by far the most common agroforestry system in water quality studies.

Although 16 of the 27 water quality studies found a significant positive influence of the agroforestry intervention, nine of the studies in riparian strips found no or mixed effects on water quality. This variation in study findings is likely to be influenced at least in part by factors such as buffer understory and width (Cole et al., 2020, Mayer

et al., 2007). While tree roots can play an important role in stabilising watercourse banks (Hubble et al., 2010), grass buffers have been found to be more effective in capturing sediments and diffuse pollutants in field runoff, leading to zoned buffers comprising a woody component and a separate uphill grass component being proposed as a potential best practice to compensate for the shading effects of the tree component on understory composition (Stutter et al., 2012, Cole et al., 2020). However, the need for wide buffers may deter farmer uptake (Hickey and Doran, 2004) and could limit any shelter or shade benefits to livestock from trees in an agroforestry context. Future research on woody riparian strips should investigate differing tree and shrub planting densities to establish integrated designs that maintain a sufficient grass understory to maximise nutrient and sediment removal at more appealing buffer widths.

2.5.4.4. Soil erosion

Twenty-eight studies quantified the effect of an agroforestry intervention on soil erosion, across five countries. Of these, 71 % found a significant positive effect of the intervention. This finding is expected given that tree planting is widely used as an appropriate strategy to stabilise slopes and reduce soil erosion globally. In particular, widespread planting has occurred on Australian and New Zealand livestock farms in recent decades in attempts to reverse the negative consequences of extensive vegetation clearing following European settlement (Mead, 1995). Only two studies found a significant negative effect of agroforestry on soil erosion in our map. These were studies of forest grazing with ungrazed forest as a control, so it is unsurprising

that the addition of livestock trampling to forest resulted in an increase in erosion, and does not negate the evidence supporting a positive influence of trees planted on pasture.

2.5.4.5. Air quality

We did not identify any studies that collected primary field data on the impact of an agroforestry intervention on air quality from a ruminant farming system. Although two air quality studies were included on the search test list (Appendix 1.1.4) these were excluded at the full-text screening stage due to not meeting the inclusion criteria. Bealey et al. (2014) was a modelling study with no primary data collection and Lin et al. (2006) looked at odour dispersion rather than air pollutants such as ammonia. Empirical data from field trials is required if agroforestry systems are to be recommended as a means to mitigate ruminant ammonia emissions.

2.5.5. Outcomes – Economics

Sixty-four studies quantified or modelled the impact of integrated livestock and trees (or other woody perennials) on farm or forestry enterprise economics https://oxlel.github.io/evidencemaps/agroforestry_economics/

Of these, the majority (73%) came from the four most represented countries (New Zealand, Australia, UK, USA) (Fig 2.3). Three-quarters of studies found a positive impact of integration on enterprise economics, compared to separate livestock and trees. However, this evidence base comprises a diversity of study types, including

case studies of return on investment from establishing an agroforestry system, mathematical modelling of optimal densities of trees and livestock under different commodity prices, and cash flow analyses. Although most of these studies focused on income streams from livestock, timber or non-timber tree products, as payments for ecosystem services become increasingly available - particularly in the form of carbon credits for CO_2 sequestration - this is likely to further increase the economic appeal of agroforestry compared to conventional agriculture (Kay et al., 2019, Kulshreshtha and Kort, 2008).

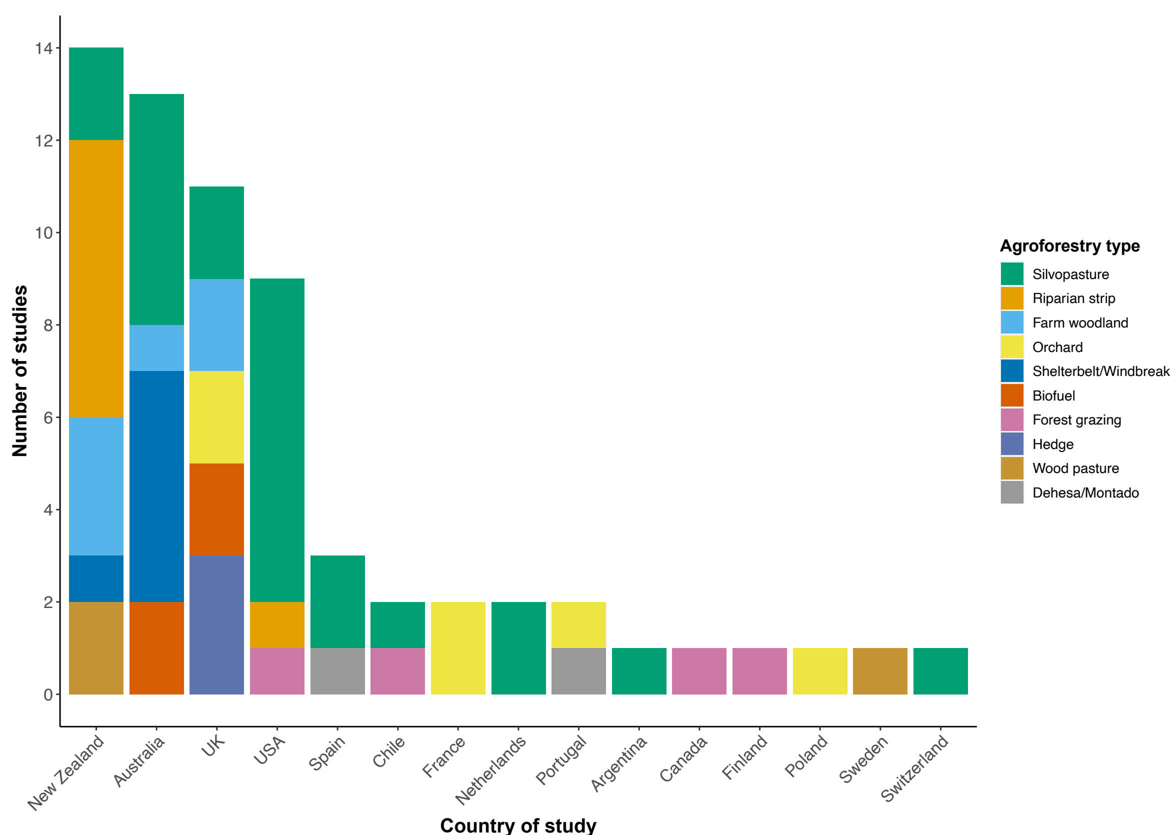

Figure 2.3. Studies that quantified or modelled the impact of agroforestry on enterprise economics (n=64) compared to one or multiple non-integrated systems, separated by agroforestry type (colours within stacked bars) and country of study.

2.5.6. Trade-offs and synergies

Our extraction of the evidence-base from these 289 studies enables the exploration of trade-offs and synergies between multiple environmental and productivity indicators, allowing previous work in this area such as Beckert et al. (2016a) to be built upon. Here we examine the relationship between agroforestry system and a) soil carbon stocks, b) pasture production, c) livestock growth, and d) heat and cold stress, milk yield and mortality, for studies with a ‘pasture without trees’ comparator (Fig 2.4). For ease of visualisation, agroforestry systems were grouped according to similarity into the categories of: i) silvopasture, ii) dehesa, montado, wood pasture or forest grazing (i.e. more semi-natural systems), and iii) shelterbelt, windbreak, riparian strip, hedge (i.e. linear field-edge systems). Relevant records from biofuel and farm woodland systems (two for soil carbon, three for pasture production, three for livestock growth) are not included in Fig 2.4.

Considering semi-natural systems (dehesa, montado, wood pasture and forest grazing), Fig 2.4a suggests that these systems typically have a positive effect on soil carbon stocks compared to pasture without trees. There is an apparent trade-off with pasture production (Fig 2.4b); no studies in our map found improved pasture growth under these systems compared to open pasture. However, livestock growth rates are typically improved in these agroforestry systems compared to open pasture (Fig 2.4c). This may indicate that there are other factors important for livestock growth such as reduced temperature stress or improved pasture quality that compensate for reduced pasture production. However, we found no studies of livestock heat or cold

stress in these systems (missing panel in Fig 2.4d), and we did not search for measures of pasture quality in this systematic map. Nevertheless, this suggests that a valuable future research contribution would be to model livestock growth in these systems compared to open pasture accounting for pasture production and quality and measures of livestock temperature stress. This could then be used to see if these productivity relationships are applicable to other temperate regions outside of the Mediterranean-type climate that many of these studies are from.

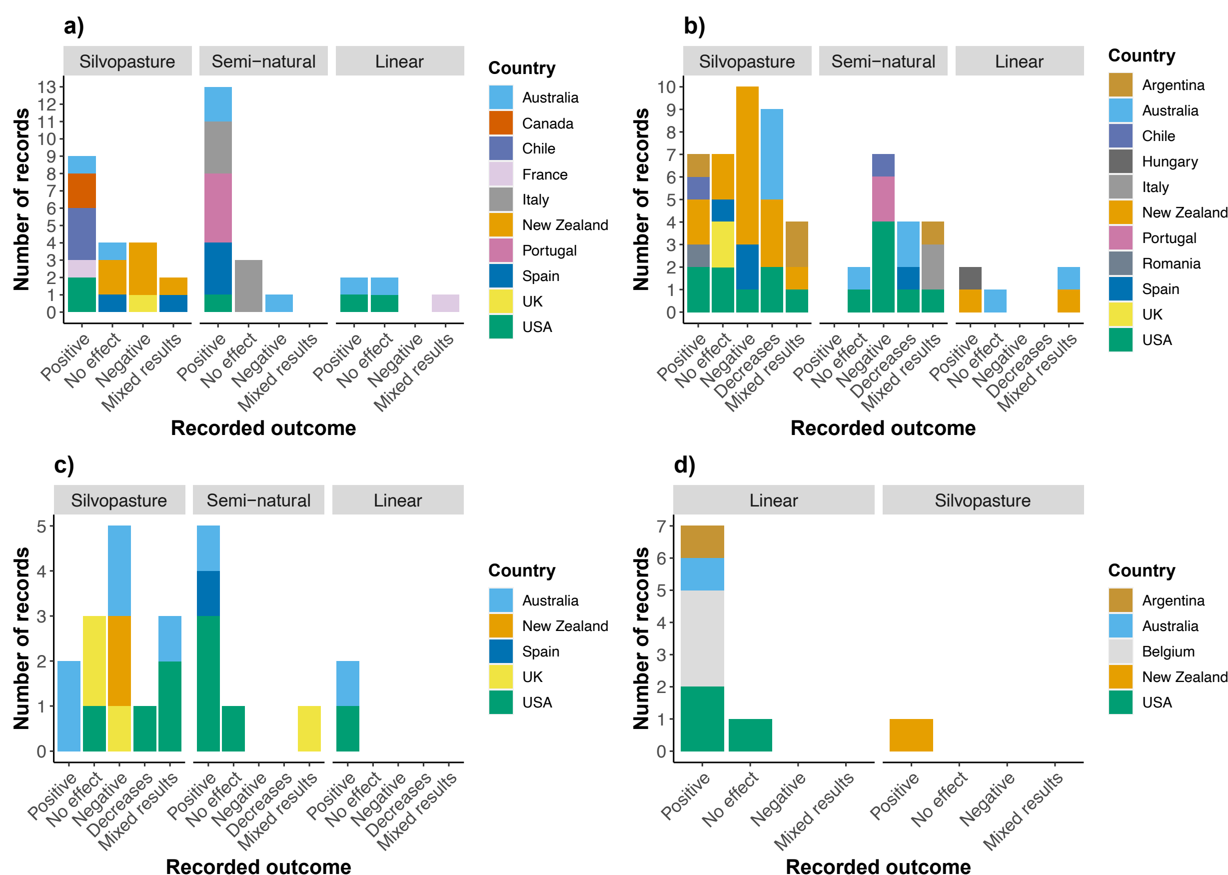

Figure 2.4. Studies with a 'pasture without tree' comparator that recorded **(a)** soil organic carbon, soil organic matter or total soil carbon (n=41), **(b)** pasture production (n=51), **(c)** livestock growth (n=23), and **(d)** livestock heat stress, cold stress, mortality or milk yield (n=9). Colours of stacked bars indicate country of study. Panel headings indicate the agroforestry systems included in each facet: 'Silvopasture' refers to trees in wide-spaced rows or clumps with herbage growing underneath, 'Semi-natural' refers to dehesa, montado,

wood pasture or forest grazing systems, and ‘Linear’ refers to shelterbelts, windbreaks, riparian strips and hedgerows. The small number of studies in farm woodland or biofuel systems are not included. In (b) and (c), the recorded outcome ‘Decreases’ was used for studies which found decreased pasture production or livestock growth, respectively, across a gradient of increased tree density, cover or proximity, whereas ‘Negative’ refers to lower production or growth under agroforestry compared to pasture without trees.

Similarly, linear systems (shelterbelts and windbreaks) appear to have a positive influence on livestock growth, heat stress, cold stress, milk yield and weather-related mortality (Fig 2.4c-d). However, there is much less evidence on the influence of these systems on pasture productivity (Fig 2.4b) (a knowledge gap identified over 20 years ago (Bird, 1998)) or soil carbon stocks (Fig 2.4a). Such field-edge agroforestry systems are also potentially suitable to improve water quantity regulation and water quality (see Sections 2.5.4.2&3). Therefore, further research on a complete basket of productivity and environmental measures would be valuable for these systems, to quantify trade-offs and synergies in delivery of these.

2.5.7. Limitations

Although our systematic map covered most major temperate regions of the world, we only included studies written in English. Much of the peer-reviewed scientific literature is now published in English, but we anticipate that this had some impact on our grey literature search. We are aware that additional search terms could have yielded more relevant studies, but they would also have included many more studies of no relevance, thereby disproportionately increasing the screening effort needed to identify relevant studies; the test set of papers gave us confidence that our search strategy balanced precision with accuracy. We based our search of temperate

regions based on the countries practicing temperate agroforestry included in Gordon et al. (2018). However, it is apparent that 'country' provides an incomplete level of climatic resolution, and we therefore recommend that further meta-analysis using this database additionally codes studies using a climate classification such as the Köppen-Geiger (Peel et al., 2007). Furthermore, we are aware that there are areas in India and China that are temperate with relevant agroforestry literature (Gordon et al., 2018), and would suggest that studies from these areas are incorporated, although we recognise that this would require a substantial additional effort to identify such studies from the very large body of non-temperate literature from these two countries.

We excluded all papers that considered the impacts of afforesting or reforesting pasture as this constitutes replacing livestock with trees not integrating them, and therefore is not agroforestry. However, some outcomes (e.g. changes in soil carbon stocks) from these studies are likely to be similar and applicable to some agroforestry systems such as small farm woodlands and shelterbelts/windbreaks. We also excluded all studies that considered shrub or tree encroachment onto rangeland because this was deemed to be not intentional integration of woody perennials with livestock. However, the outcomes (e.g. pasture productivity, carbon stocks) under these systems are arguably applicable to some temperate agroforestry systems.

2.6. Conclusions

We identified, through a systematic mapping process, a substantial evidence base (289 studies) on the productivity, environmental and economic impacts of integrating agroforestry into temperate sheep and cattle farming systems, creating an interactive resource with applications across temperate regions. It is clear that adopting agroforestry has the potential to sequester carbon, reduce soil erosion, and, with appropriate management, improve water quantity and quality regulation. However, the impact of agroforestry systems on pasture productivity and livestock growth are variable, and livestock productivity measures such as heat and cold stress and weather-related mortality have been little-studied. Although we suggest some possible trade-offs and synergies between agroforestry system type and the delivery of environmental and productivity benefits, further meta-analyses are required to validate these suggested trends for already well-studied outcomes, complemented by further field research where data is inadequate. Although widespread economic benefits of agroforestry adoption are reported in the literature, studies are generally highly context specific. This systematic map can be applied across temperate regions by researchers, policy-makers and practitioners as a resource to inform promotion and implementation of agroforestry practices that increase the sustainability of ruminant livestock production.

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Chapter 3. Temperate Regenerative Agriculture practices increase soil carbon but not crop yield – a meta-analysis

3.1. Summary

This chapter presents the results of my meta-analysis of data extracted from studies identified in a systematic literature review. I focused on the RA practices of reducing tillage intensity, cover cropping and ley-arable rotations in temperate oceanic arable systems. By identifying paired SOC-yield observations and subsequently analysing these using Bayesian hierarchical models, I was able to demonstrate that reduced tillage intensity and ley-arable systems increase SOC concentration but not crop yield. This further addresses my first aim in this thesis, and suggests that although these practices may be suitable for enhancing SOC they do not provide a win-win between increasing SOC and crop yield.

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Temperate Regenerative Agriculture practices increase soil carbon but not crop yield – a meta-analysis

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3.2. Abstract

Regenerative Agriculture (RA) claims to build soil organic carbon (SOC) and increase crop yields through simultaneous adoption of a suite of management practices which restore soil health. However, this claim is largely unevidenced as few studies of fully integrated regenerative systems are currently available. As a first step to addressing this knowledge gap, we here examine three practices now being promoted as part of RA: reducing tillage intensity, cover cropping and including a grass-based phase in arable rotations (ley-arable rotations). Our Bayesian meta-analysis of 195 paired SOC and crop yield observations from a systematic review of published studies finds statistically significant increases in SOC concentration for reduced tillage intensity (0.06 g C.100g^{-1}) and ley-arable rotations (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 reduce yield during cropping years, although we find no evidence of a win-win between increasing SOC and enhanced agricultural productivity following adoption. While future work should evaluate the net greenhouse gas emission implications of each practice and investigate the potential for synergistic effects if RA practices are adopted in combination, our results give land managers and policy makers confidence to further adopt these practices without loss of crop yield.

3.3. Introduction

There is longstanding awareness of the need to adopt alternative management practices on agricultural land to maintain or improve productivity while preventing soil degradation, expressed in management paradigms such as organic farming, agroecology, climate-smart agriculture, conservation agriculture and sustainable intensification (Lampkin et al., 2015, TABLE, 2021, Lal, 2015, Godfray and Garnett, 2014, Descheemaeker et al., 2020). These frequently draw on similar suites of management practices, which in arable systems include reducing soil tillage intensity in seedbed preparation, growing over-winter cover crops to protect soils between arable crops, and integrating multi-year grass-based leys into arable rotations to build fertility (Table 3.1). These three practices can increase soil organic carbon (SOC) (West and Post, 2002, Sanden et al., 2018, Haddaway et al., 2017a, McClelland et al., 2021, Jian et al., 2020, Poeplau and Don, 2015b, Conant et al., 2017), making them increasingly of interest due to the potential for farmland soil carbon sequestration to contribute to climate change mitigation (Lal, 2004, Poulton et

al., 2018, IPCC, 2019). However, their impact on crop yields is less clear, with previous syntheses finding variable effects (Sanden et al., 2018, Sun et al., 2020, Abdalla et al., 2019b, Huang et al., 2018, Pittelkow et al., 2015b) and little work to date for ley-arable rotations.

Table 3.1. 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 (Haddaway et al., 2017a)	Improved soil structure and biological activity, decreased risk of soil erosion (Powlson et al., 2014), improved water quality (Skaalsveen et al., 2019)	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 (Powlson et al., 2014).
Cover crops	Catch crops, green manure	Inclusion of temporary fast-growing plants to cover the soil between arable crops (Poeplau and Don, 2015a) typically over winter, present for under a year.	Reduce nitrogen leaching (Abdalla et al., 2019a), enhance soil microbiota (Kim et al., 2020)	Inclusion of legumes can increase nitrous oxide emissions (Muhammad et al., 2019), 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 (Lemaire et al., 2015)	Ley phase builds fertility for following arable crops and can provide livestock fodder (Elliot, 1908, Turner, 1951, Stapledon and Davies, 1948, Martin et al., 2020)	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.

Alternative land management practices such as these are currently receiving further attention as part of the Regenerative Agriculture (RA) paradigm. This has been defined as “an approach to farming that uses soil conservation as the entry point to

regenerate and contribute to multiple ecosystem services" (Schreefel et al., 2020) and is rapidly gaining popularity among land managers, policy makers, NGOs and corporates (Burgess et al., 2019, Giller et al., 2021, Newton et al., 2020), in part due to an appealing proposed win-win between increasing SOC and crop yields (Moyer et al., 2020). However, there is currently limited evidence to verify this claim of RA from whole-system adoption in temperate regions. Although a substantial evidence base does exist for individual management actions (Table 3.1) now being adopted as part of a regenerative approach, existing syntheses typically only consider the impact on SOC (Bai et al., 2019, Crystal-Ornelas et al., 2021, McClelland et al., 2021, Morugán-Coronado et al., 2020) or yield (Pittelkow et al., 2015a, Pittelkow et al., 2015b, Su et al., 2021a, Su et al., 2021b) of these practices. Verifying whether such practices can deliver a win-win requires analysis of *paired* SOC and yield observations and remains a key knowledge gap. Further, although evidence to date suggests that crop yield tends to increase with SOC, particularly at low concentrations (Loveland and Webb, 2003, Oldfield et al., 2019), it is still unclear whether this relationship varies between different practices that build SOC (Ingram et al., 2016, Henriksen et al., 2011).

This study aimed to fill these knowledge gaps by using paired SOC-yield observations analysed across multiple interventions to investigate the influence of three management practices (reduced tillage intensity, cover cropping and ley-arable rotations, Table 3.1) on SOC and crop yield in temperate arable systems.

We addressed this aim by undertaking two interlinked objectives:

1. Determination of whether different practices currently promoted as part of RA simultaneously increase SOC and crop yield in temperate oceanic arable systems
2. Understanding the relationship between SOC and yield across different management interventions

We assembled a database of 195 paired observations of SOC and crop yield across tillage, cover crop and ley-arable interventions for quantitative meta-analysis from relevant studies conducted in regions with a temperate oceanic climate (Köppen-Geiger Cfb) using systematic review methods. We then used this database to parametrise Bayesian multivariate meta-analyses of SOC and yield. Our findings indicate that this approach can deliver important insights into the influence of agricultural management practices on soil carbon and crop productivity.

3.4. Methods

3.4.1. Systematic review

We followed the Collaboration for Environmental Evidence guidelines (CEE, 2018) 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) framing (Table A2.1). Full details of our systematic review following the Reporting standards for Systematic Evidence

Syntheses (ROSES) framework (Haddaway et al., 2017b) are given in Appendix 2.1, building on the methods of Haddaway et al. (Haddaway et al., 2017a, Haddaway et al., 2015). All data extracted from relevant studies and further supplementary files are available online (Jordon, 2021).

Previously, Haddaway et al. (2015) 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 (Haddaway et al., 2017a). We utilised, expanded and updated these previous searches, focusing on tillage, cover crops and ley-arable interventions in temperate oceanic regions. Climatic and wider environmental variation can be accounted for in meta-analyses by: i) including climate zone or environmental variables as a predictors in the meta-analytical model (Sun et al., 2020, Angers and Eriksen-Hamel, 2008, West and Post, 2002); ii) restricting the scope of the meta-analysis to a particular climatic or geographic region (Sanden et al., 2018, Van den Putte et al., 2010, Körschens et al., 2013, González-Sánchez et al., 2012); or iii) a combination of the two (Haddaway et al., 2017a, McClelland et al., 2021). We selected approach (ii) here, because we decided it was most appropriate for ascertaining findings generalisable to a specific context of interest and has strong precedent in previous syntheses.

We considered individual interventions, focusing on measures that are likely to affect yield predominantly through soil properties, unlike RA practices such as silvoarable which impact crop yield through competition for resources (Ivezić et al., 2021). We

also selected practices which had sufficient evidence available for quantitative synthesis, which meant excluding practices such as pasture cropping (Millar and Badgery, 2009). Our final list of interventions considered here are no or reduced soil tillage in seedbed preparation for crop establishment, overwinter cover cropping in place of crop stubble with exposed soil, and incorporating a grass-based ley phase into arable rotations (Table 3.1).

We conducted searches in Web of Science, CAB Abstracts and Scopus (details in Table A2.2, Appendix 2.1.1) and screened records at title, abstract and full text levels using pre-determined inclusion and exclusion criteria (Table A2.3), with consistency checking between reviewers (Appendix 2.1.2). Data from relevant studies was extracted to a spreadsheet (Appendix 2.1.3), and assigned a critical appraisal score reflecting the study quality (Table A2.4). 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 by studies in our systematic review as stocks ($t.ha^{-1}$) we converted these to concentration ($g.100g^{-1}$) using soil bulk density measurements presented alongside these in the same article (Table A2.5). 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 using conventional formulae (Table A2.5). If measures of variability presented were between-treatment only, these were not

extracted. Where desired data was missing from articles (Table A2.6), we attempted to contact the corresponding author with a request for data (Appendix 2.1.4).

Our systematic review resulted in a database of 30 articles containing 40 studies across 10 countries with temperate oceanic regions (Fig 3.1, A2.1). From this, we extracted 195 paired observations of SOC and crop yield across tillage, cover crop and ley-arable interventions for quantitative meta-analysis. Although including studies that measured SOC or yield separately would have increased data availability, this would not have provided the same strength of inference in identifying synergies or trade-offs between these outcomes across management practices.

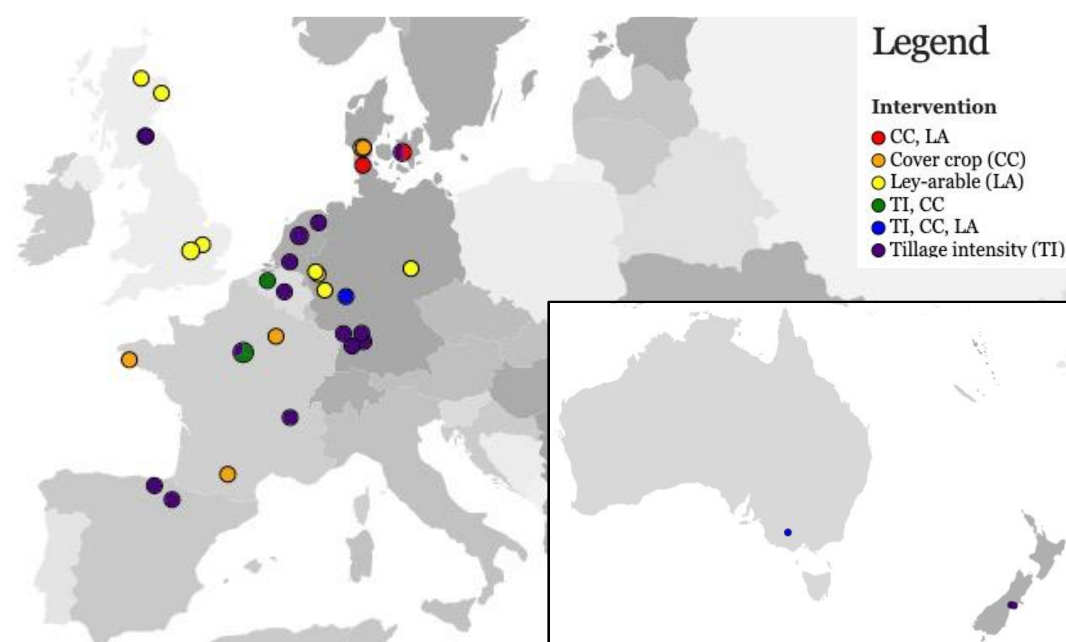

Figure 3.1. Systematic map. 40 relevant studies identified by systematic review process for inclusion in meta-analysis, created using the Thalloo framework(Martin, 2018). Position of pie charts reflects study locations (degrees decimal coordinates), size of pie charts is proportional to the number of 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/

3.4.2. Meta-analysis

To analyse the dataset assembled by our systematic review, we fitted Bayesian multivariate hierarchical (i.e. random effects) meta-analyses using the *brms* package in R version 4.0.3 (Bürkner, 2017, Bürkner, 2018, Stan Development Team, 2019, R Core Team, 2020). Our R code is available online (Jordon, 2021) and further details of the analysis approach and model summary outputs are given in Appendix 2.2, including details of model priors used, tests for model convergence and publication bias, and how figures were plotted. In the following sections, we describe the models fitted, how response and explanatory variables are expressed, and sensitivity analyses we conducted to determine the influence of data quality and availability on our results.

We did not compute comparative effect size metrics (i.e. between treatments, or between control and treatment), instead directly analysing the outcome mean per treatment reported by studies in our systematic review. This is 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.

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* corresponds to ‘endline’ estimate of soil organic carbon concentration ($g.100g^{-1}$), accounting for its standard error,
- *$Yield_E$* corresponds to ‘endline’ estimate of crop yield ($t.ha^{-1}$), accounting for its standard error,
- *Tillage* is a categorical variable of tillage regime; conventional tillage (reference category), reduced tillage or no tillage, with variables dummy coded,
- *Cover crop* reflects the 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* is the duration (years) of the ley-phase of the arable rotation (reference = 0, i.e. arable-only rotation),

- *Duration* corresponds to the total duration of study (years), from implementation of treatment interventions to the most recent data presented in the original article,
- *Latitude* is the absolute Latitude of the study site, in decimal degrees,
- *Clay* is the soil clay content (%) of the study site,
- *Depth* provides the soil sampling depth (cm) soil to measure SOC,
- SOC_B corresponds to the true baseline, i.e. pre-intervention, estimate of soil organic carbon concentration ($g.100g^{-1}$),
- *Crop* indicates the crop harvested to give $Yield_E$ measurement,
- *Unique study ID* is an ID code we generated and included as a random effect to account for the hierarchical structure of the data

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. We used Bayes R^2 to estimate the proportion of variation explained by the overall model and fixed effects only (Gelman et al., 2019). All models fitted explained a large proportion of variation in the data, with Bayes R^2 ranging from 0.85-0.99 and 0.34-0.94 for the full model and fixed effects respectively (Table 3.2).

We chose to represent *Ley* duration in years to capture the duration-dependence of sward and root development during the ley phase. However, a proportion was used for *Cover crops* because these were less than a year in duration, typically sown after one autumn-harvested arable crop and terminated before the following spring-sown crop, resulting in little difference in duration of individual cover crop events within or

between studies. Non-intervention-specific predictors (*Duration*, *Latitude*, *Clay*, *Depth*, SOC_B and *Crop*) were included based on previous work which identified these factors as influencing SOC and/or yield (Haddaway et al., 2017a, Poeplau and Don, 2015a, Jian et al., 2020, Pittelkow et al., 2015b, Schweizer et al., 2021). Where missing in the original article, clay data were extracted from the WISE30sec harmonised global soil property database (Batjes, 2016) using study site coordinates. We centred the *Duration*, *Latitude*, *Clay*, *Depth* 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 the arable rotation).

Although climate (e.g. precipitation, temperature) and intervention management variables (e.g. cover crop planting and termination dates, tillage depth, fertiliser regime) have also been found to be important determinants of SOC and yield in previous syntheses (Pittelkow et al., 2015b, Haddaway et al., 2017a, McClelland et al., 2021, Bai et al., 2019), we were unable to include these here due to limited data availability. There were both too few observations to identify these predictors in analysis and insufficient studies presenting information on these variables. However, by restricting our meta-analysis to temperate oceanic regions (Köppen-Geiger Cfb), we were able to minimise the influence of climate variables on our results because the study sites included are all located in a similar climatic zone.

Many studies did not present both SOC and crop yield results factorially across fertiliser treatments or failed to specify fertiliser applications. As a result, we were unable to include fertiliser as a predictor in the yield analysis. In addition, it would have been desirable to account for soil properties such as texture (*Clay*) and organic matter content (SOC_B as a proxy) in the yield analysis, but the large number of levels in the *Crop* categorical variable restricted our ability to include other predictors. However, the results of the yield model fitted on data where errors were present rather than imputed (Table 3.2) had a Bayes R^2 for the fixed effects of 0.94, suggesting most variation in the data was captured by existing predictors. Lower fixed effects R^2 for models with imputed errors are likely due to a combination of uncertainty introduced by the imputation process and studies with missing errors potentially being more heterogenous.

We used SOC concentration ($g.100g^{-1}$) in our analysis to allow us to investigate the relationship between crop yield and soil carbon across studies. 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, which differed between studies, and soil bulk density, which differed both between studies and treatments within studies. There was limited availability of treatment-specific bulk density measurements in studies (Table A2.6) to transform SOC concentrations (more-commonly reported) to stocks.

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 calculated average soil carbon to 30 cm (weighted by the soil thickness of each stratified sample where this differed), such that each experimental 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 our objectives in the analyses here, although this has recently been empirically addressed elsewhere (Meurer et al., 2018, Xiao et al., 2020).

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 predictor terms. 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.

3.4.2.1. Imputation and sensitivity analyses

Of the 195 paired observations of SOC and crop yield identified in our systematic review, 66 had within-treatment standard errors presented or calculable for both SOC_E and $Yield_E$. In contrast, 78 data 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. Unless values are missing at random, discarding data with missing values risks biasing the meta-analysis (Weir et al., 2018). 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 (Lajeunesse, 2013). 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* (van Buuren and Groothuis-Oudshoorn, 2011).

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 A2.4, Appendix 2.1.3) 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. Finally, study duration is known to influence the ability to detect changes in SOC (Smith, 2004). Although we did not apply a minimum study duration in our meta-analysis unlike previous meta-analyses

(Haddaway et al., 2017a), we repeated our analysis excluding studies with durations less than ten years to detect whether our results were affected by this. Therefore, we conducted a total of six analyses with different levels of data availability (due to imputation or sensitivity analyses), as follows:

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 15.1 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 26 studies, average duration 12.5 years)
6. SD: same as (4), but studies with durations of less than 10 years were excluded (105 data from 23 studies, average duration 18.6 years)

We present model outputs from all analyses in Table 3.2 for comparison and plot model effects for the practice predictors in Fig A2.6. We use the results from EIBI

throughout the paper and in Figs 3.2 and A2.5, as this includes the greatest number of observations while accounting for baseline soil carbon in the SOC analysis. We discuss the sensitivity of the EIBI results to data availability and quality below.

3.5. Results

We found that the RA management practice of converting from conventional full-inversion tillage to no tillage increased SOC concentration by 0.06 g $C.100g^{-1}$ (95% Credible Intervals, CI, [0.00, 0.11]), and reduced-tillage by 0.09 [0.03, 0.14], over an average study duration of 15 years (Table 3.2, Fig 3.2a), without negatively impacting crop yield (95% CI of effect size included 0, Table 3.2, Fig 3.2b). These data were extracted from a total of 106 tillage intensity treatments (Fig A2.2) from 23 studies that measured the effect of changing tillage intensity on SOC and yield (Fig A2.1) identified by our systematic review.

Twelve studies investigated incorporating cover crops into arable rotations (Fig A2.1), providing 79 observations of SOC and yield. From these, we did not find a significant effect of cover cropping in every year of an arable rotation on SOC (95% CI [-0.0, 0.15] g $C.100g^{-1}$) or yield (Table 3.2, Fig 3.2c-d) compared to when no cover crops were present.

Regarding integrating a grass-based ley phase into arable rotations, we found 13 studies that reported SOC and yield (Fig A2.1). This resulted in 70 data points with ley duration ranging from zero to six years within the rotation (Fig A2.4). We found

that inclusion of a one-year ley phase increased SOC concentration by 0.05 g C.100g^{-1} (95% CI [0.03 to 0.08] Table 3.2, Fig 3.2e) 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% CI of effect size include 0, Table 3.2, Fig 3.2f). Although not explicitly quantified here, the inclusion of a grass-based ley in a rotation results in a complete absence of arable crop yield in those years, so note that the total crop output (e.g. tonnes of cereal) of the overall rotation is reduced in proportion to the duration of the ley-phase in ley-arable rotations.

We also found that differences in study duration and absolute latitude had no effect on SOC concentration or crop yield (Table 3.2). In addition, soil clay content (%) did not significantly predict SOC concentration (Table 3.2). SOC concentration decreased by 0.05 g C.100g^{-1} (95% CI [-0.09, -0.02], Table 3.2) 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.

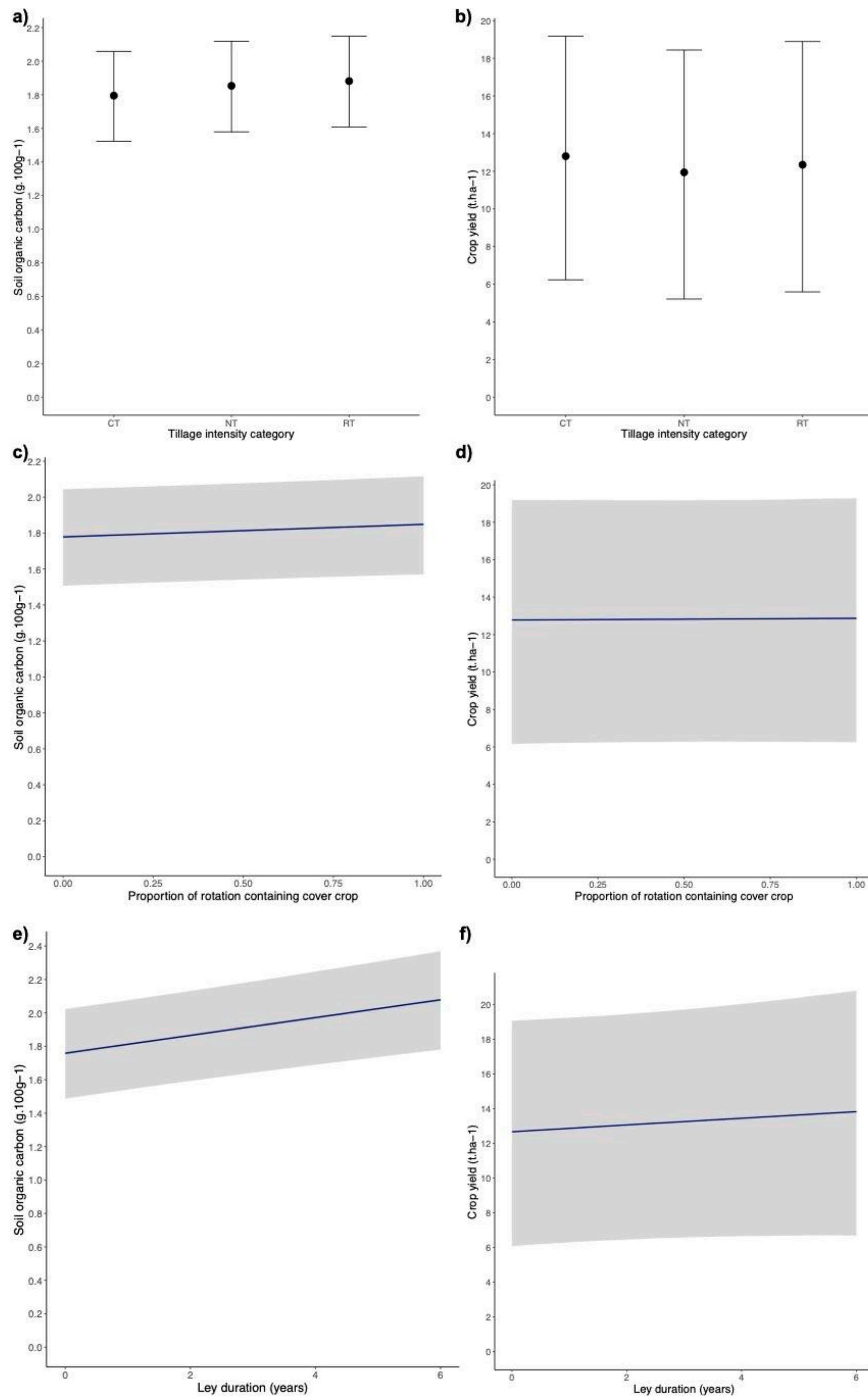

Figure 3.2. Effects of interventions on SOC concentration and crop yield. Conditional effects of (**a-b**) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (**c-d**) cover cropping, proportion of years present in arable rotation, (**e-f**) ley-arable rotations, length of ley phase within the arable rotation in years, for soil organic carbon (g.100g^{-1}) and arable 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).

Table 3.2. Estimates of soil organic carbon (g.100g^{-1}) and arable crop yield (t.ha^{-1}) following implementation of no or reduced tillage, cover crops or ley-arable rotations. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. Study duration, absolute latitude, baseline SOC, % clay and soil sampling depth were centred before the analysis to assist interpretation of model output. The Intercept corresponds to 'conventional' practice (reference category: conventional tillage, no cover cropping or ley phase) for these centred predictor values, with other columns showing the difference from this Intercept for one increment in the unit of the respective predictor. Results are presented for six iterations of the analysis with different levels of data availability and quality (see Methods for further details), with EIBI results discussed in the text. Full model summary outputs are provided in Appendix 2.2.2. Effect sizes for Practice predictors across all models are visualised in Fig A2.6 to facilitate model comparison.

Model	Response	Intercept†	No till	Reduced till	Cover crops‡	Ley-arable††	Study duration	Latitude‡‡	SOC baseline	Soil % clay	Soil sampling depth	Standard deviation parameters		SOC-yield residual correlation	R^2		n	
												Within studies	Between studies		Whole model	Fixed effects	Data	Studies
EP: Error present	SOC	1.52 [1.28, 1.76]	0.11 [0.03, 0.18]*	0.10 [0.02, 0.18]*	0.07 [-0.06, 0.20]	0.04 [0.01, 0.06]*	0.00 [-0.01, 0.01]	0.05 [-0.05, 0.13]	-	-0.02 [-0.07, 0.01]	-0.05 [-0.10, 0.00]	0.07 [0.05, 0.09]	0.45 [0.29, 0.73]	0.33 [0.03, 0.57]*	0.969	0.528	66	16
	Yield	70.98 [63.9, 77.9]	-1.85 [-6.36, 2.53]	-0.70 [-5.39, 4.11]	-1.72 [-9.01, 5.59]	0.23 [-0.75, 1.23]	-0.29 [-0.67, 0.12]	0.14 [-1.03, 1.34]	-	-	-	5.10 [4.14, 6.29]	1.20 [0.04, 3.81]		0.947	0.944		
EI: Error imputed	SOC	1.75 [1.47, 2.02]	0.06 [0.00, 0.11]*	0.09 [0.03, 0.14]*	0.06 [-0.01, 0.13]	0.05 [0.03, 0.08]*	0.00 [-0.00, 0.00]	0.04 [-0.04, 0.12]	-	-0.04 [-0.08, 0.00]	-0.06 [-0.09, -0.02]*	0.10 [0.08, 0.12]	0.86 [0.67, 1.11]	0.15 [-0.01, 0.31]	0.983	0.435	195	40
	Yield	12.7 [6.01, 19.1]	-0.85 [-2.37, 0.68]	-0.46 [-1.93, 1.00]	0.09 [-1.83, 2.03]	0.20 [-0.38, 0.77]	-0.05 [-0.16, 0.06]	0.33 [-0.87, 1.59]	-	-	-	2.99 [2.63, 3.40]	11.5 [8.90, 15.0]		0.946	0.478		
EIBP: Baseline present, error imputed	SOC	1.30 [1.08, 1.51]	0.07 [0.00, 0.14]*	0.02 [-0.05, 0.09]	0.06 [-0.02, 0.15]	0.05 [0.02, 0.08]*	0.00 [-0.00 0.00]	0.03 [-0.04, 0.09]	0.76 [0.36, 1.13]*	0.01 [-0.05, 0.05]	-0.01 [-0.07, 0.04]	0.08 [0.05, 0.10]	0.34 [0.21, 0.58]	0.20 [-0.06, 0.43]	0.980	0.778	79	14
	Yield	9.28 [3.38, 14.9]	-1.18 [-2.77, 0.38]	-0.12 [-1.77, 1.55]	0.04 [-2.08, 2.21]	-0.16 [-0.94, 0.54]	-0.03 [-0.10, 0.05]	0.10 [-0.57, 0.74]	-	-	-	2.09 [1.46, 2.73]	3.43 [1.81, 6.05]		0.851	0.669		
EIBI: Baseline and error imputed	SOC	1.73 [1.46, 2.00]	0.06 [0.00, 0.11]*	0.09 [0.03, 0.14]*	0.07 [-0.01, 0.15]	0.05 [0.03, 0.08]*	0.00 [-0.00, 0.00]	0.04 [-0.04, 0.12]	0.06 [-0.10, 0.19]	-0.03 [-0.07, 0.00]	-0.05 [-0.09, -0.02]*	0.10 [0.08, 0.12]	0.84 [0.64, 1.10]	0.12 [-0.07, 0.30]	0.983	0.451	195	40
	Yield	12.6 [6.01, 19.1]	-0.86 [-2.39, 0.66]	-0.46 [-1.94, 1.02]	0.09 [-1.84, 2.04]	0.19 [-0.38, 0.77]	-0.05 [-0.16, 0.06]	0.35 [-0.88, 1.59]	-	-	-	2.99 [2.63, 3.40]	11.5 [8.87, 15.0]		0.946	0.476		
Sensitivity analysis: critical appraisal [CA]	SOC	1.47 [1.22, 1.71]	0.04 [-0.01, 0.10]	0.04 [-0.01, 0.09]	0.06 [-0.00, 0.12]	0.05 [0.03, 0.07]*	0.00 [-0.00, 0.00]	0.02 [-0.07, 0.10]	0.13 [-0.04, 0.42]	-0.03 [-0.07, 0.01]	-0.07 [-0.10, -0.03]*	0.08 [0.06, 0.10]	0.61 [0.45, 0.85]	0.10 [-0.08, 0.27]	0.981	0.568	144	26
	Yield	6.70 [3.64, 9.57]	-0.76 [-1.76, 0.24]	-0.26 [-1.21, 0.69]	0.23 [-1.00, 1.45]	0.17 [-0.14, 0.49]	-0.03 [-0.08, 0.02]	0.07 [-0.41, 0.53]	-	-	-	1.64 [1.42, 1.89]	3.26 [2.19, 4.87]		0.975	0.889		
Sensitivity analysis: study duration [SD]	SOC	1.59 [1.16, 2.01]	0.09 [0.02, 0.16]*	0.09 [0.03, 0.16]*	0.06 [-0.04, 0.15]	0.07 [0.04, 0.10]*	-	0.09 [-0.04, 0.21]	-0.01 [-0.14, 0.10]	-0.01 [-0.06, 0.05]	-0.03 [-0.08, 0.03]	0.09 [0.07, 0.11]	1.00 [0.72, 1.43]	0.35 [0.12, 0.55]*	0.986	0.373	105	23
	Yield	8.48 [6.30, 10.7]	-0.01 [-0.52, 0.47]	0.13 [-0.37, 0.64]	0.07 [-0.62, 0.74]	0.24 [0.04, 0.43]*	-	0.20 [-0.42, 0.82]	-	-	-	0.55 [0.42, 0.73]	3.79 [2.67, 5.49]		0.948	0.336		

†Conventional tillage and no cover crops or ley-phase in rotation

[‡]Estimated effect where cover crops are present in every year of the rotation
[††]Estimated effect of one year of ley in a rotation, would increase as multiple of total ley duration within rotation
[‡‡]Absolute latitude

3.5.1. Sensitivity analyses

We ran six iterations of our analysis accounting 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 3.2, Fig A2.6). Where baseline SOC values were reported in studies, this was a significant predictor of endline SOC (EIBP, Table 3.2), with an increase in endline values of 0.76 g $C.100g^{-1}$, 95% CI [0.36, 1.13], 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 3.2), 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 explaining 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 3.2, Fig A2.6). Our findings were also robust to exclusion of short-duration studies (less than 10 years, SD analysis), apart from the effect of ley duration on yield which increased 0.24 $t.ha^{-1}$ per year of ley in the rotation in this analysis (95% CI [0.04, 0.43], Table 3.2, Fig A2.6).

3.5.2. SOC-yield relationship

Despite finding a positive correlation between SOC and yield as expected overall, our univariate analysis of crop yield did not identify any significant interactions between interventions and SOC (Table A2.8); i.e. the relationship between SOC and yield did not differ when each intervention was adopted or between interventions (Fig 3.3). We found a significant residual correlation between SOC concentration and crop yield in the EP and SD models (i.e. after all other predictors were accounted for), but this was not retained in other analyses (Table 3.2).

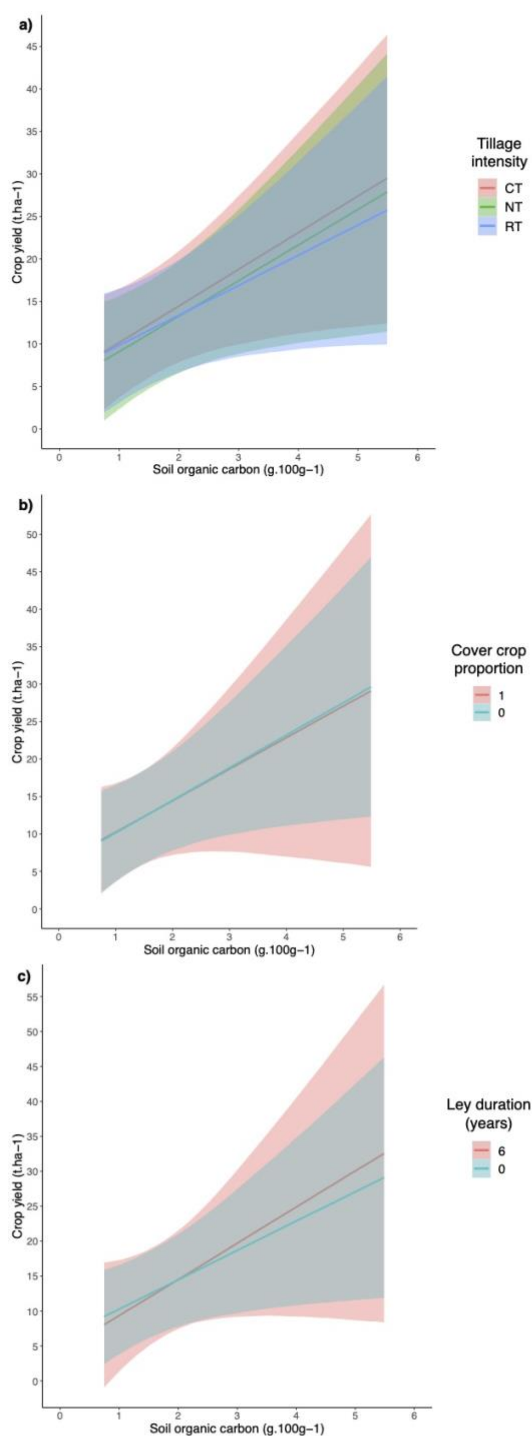

Figure 3.3. Differences in correlation between soil carbon and yield between levels of adoption of each intervention. Conditional effects of interactions between soil organic carbon (g.100g^{-1}) and (**a**) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (b) cover cropping, proportion of years present in arable rotation, (**c**) ley-arable rotations, length of ley phase within the arable rotation in years, on arable 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).

3.6. Discussion

Results from our meta-analysis demonstrate that reducing tillage intensity and incorporating temporary grass-based leys into arable rotations can significantly enhance SOC without negatively impacting yield during years with arable crops. In comparison, our results indicate that cover cropping does not increase SOC. Overall, the results from our meta-analysis do not verify the claim that RA practices can simultaneously increase SOC and crop yield (Moyer et al., 2020) in temperate oceanic regions. Nevertheless, our demonstration of the potential for increases in SOC without yield loss supports further adoption of these practices as part of strategies to restore soil health and mitigate climate change. Regarding our second objective, we do not find any evidence of different SOC-yield relationships between interventions, implying that changes in soil properties or other aspects of management between interventions is either minimal or does not impact yield.

Increased SOC following a reduction in tillage intensity has also been found in previous analyses from Europe (Sanden et al., 2018, Smith et al., 1998), temperate regions (Haddaway et al., 2017a) and globally (West and Post, 2002). Explanations as to why this RA management practice results in increased SOC include enhanced soil aggregation and lower soil temperatures due to reduced disturbance, both of which protect SOC from degradation (Huang et al., 2018). Accumulation of crop residues at the soil surface, which will occur with reduced tillage particularly if crop residues are not removed as straw, can also contribute to higher soil carbon concentration measurements when only shallow sampling depths (≤30 cm) are

considered (Meurer et al., 2018). Such shallow sampling is present in our dataset and can lead to an overestimation of the SOC gains of reducing tillage intensity. Research that has accounted for this through deeper soil sampling has found a redistribution of SOC within the soil profile and smaller overall increase (Meurer et al., 2018, Xiao et al., 2020, Powlson et al., 2014). Our finding that reduced tillage may increase SOC more than no tillage is interesting, although there is substantial overlap between the Credible Intervals and a small magnitude of difference between these effects (Table 3.2, Fig 3.2a). As such, the seemingly higher SOC in RT treatments may be because few studies considered both NT and RT.

Regarding yields, previous syntheses 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 (Pittelkow et al., 2015b, Huang et al., 2018, Sun et al., 2020). Yield gains are typically only found in water-limited conditions in dry climates due to the moisture retention benefits of surface crop residues and undisturbed soil aggregates (Pittelkow et al., 2015b, Huang et al., 2018, Sun et al., 2020). In contrast to previous European analyses (Sanden et al., 2018, Zavattaro et al., 2015), 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 agree with Sun et al. (2020) that no-till with residue retention and crop rotation can increase SOC without changing crop yield in humid regions.

We found no effect of interannual cover cropping on SOC or yield, in line with other work from Europe (Sanden et al., 2018). Although cover crops can build SOC through increasing plant residue inputs to soil, this mechanism may be less effective in the temperate oceanic regions we considered here due to three factors. Firstly, there are typically high rates of fertiliser application in northwest Europe, New Zealand and southeast Australia where the studies analysed here were conducted, which may reduce the benefits of cover crops. Secondly, higher latitudes and lower temperatures in these regions likely limit the cover crop growing season resulting in poor plant development. Thirdly, some cover crops grown in studies analysed here were grass-based rather than legume or mixed, resulting in a higher C:N ratio which potentially increases the time taken to build SOC (Poeplau and Don, 2015a, Abdalla et al., 2019a, Jian et al., 2020).

In terms of impact on yield, leguminous cover crops can fix nitrogen and could therefore enhance soil fertility while non-legumes may help retain existing soil nutrients. These could act to increase arable crop yield, but cover crops may also compete with subsequent arable crops for nutrients particularly if they are not terminated correctly. These competing mechanisms are reflected in previous syntheses which have reported inconsistent effects of cover crops on yield within the commonly-used categories of legume, non-legume and mixed (Abdalla et al., 2019a). Further work is required to adequately explain differences in reported trends.

Our finding that including a grass-based ley phase in temperate oceanic arable rotations increases SOC was expected in line with previous studies (Conant et al., 2017, West and Post, 2002). There are likely multiple mechanistic reasons for this increase in soil carbon. Firstly, better-established root systems increase plant residue inputs, particularly from root litter. Secondly, a temporary break from cultivation protects SOC from degradation. Thirdly, soil microbiological activity is enhanced, which improves the stability of soil aggregates and so further protects SOC from degradation during cultivation in the arable phase of the rotation (Soussana et al., 2004, Conant et al., 2001). Previous work has demonstrated that permanent conversion of cropland to grassland typically increases SOC (Guo and Gifford, 2002, Conant et al., 2017, Smith, 2014). It is therefore likely that ley-arable rotations will fluctuate between increasing SOC during the ley phase and declines during the arable phase, resulting in soil carbon values that are higher than continuous cropping (Lemaire et al., 2015, Soussana et al., 2004, Hu and Chabbi, 2022, Conant et al., 2017, West and Post, 2002).

We did not find an increase in crop yields following a ley-phase in arable rotations, which was unexpected given the long-established fertility building properties of temporary leys driving their current widespread adoption in organic arable systems (Lemaire et al., 2015, Elliot, 1908, Turner, 1951, Stapledon and Davies, 1948, Berdeni et al., 2021). However, it may be that the fertility benefits of leys take several years to translate into improved yields, given our analysis excluding studies shorter than 10 years did identify a positive relationship between including ley in the rotation

and crop yield (SD analysis, Table 3.2). There is also a 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 (Johnston et al., 1994, Rasmussen et al., 2008). In terms of practical limitations, ley-arable rotations require a proportion of total cropland to be taken out of arable crop production each year to establish leys. This potentially results in compensatory cultivation elsewhere leading to overall SOC losses (Carlton et al., 2010), necessitating either a reorientation of livestock feeding to reduce the area of arable cropland required per year (Karlsson and Röös, 2019) or other measures to reduce overall demand for animal products such as waste reduction or dietary change (Springmann et al., 2018).

Despite our findings that some RA management practices can significantly increase SOC, there are important limits to the generalisability of our findings to RA in practice. Firstly, we considered individual interventions that can be part of a RA approach, rather than comparing 'regenerative' systems that simultaneously implement multiple interventions with 'conventional' systems. This was due to the current lack of studies specifically evaluating RA systems, although our method for analysis enabled us to best represent studies that implemented multiple interventions factorially. On the one hand, this prevented us from identifying potential synergistic benefits of these interventions in combination, but conversely masked any difficulties of implementing these simultaneously in a real-world context. There are also other interventions that can be adopted as part of an RA approach that we

did not include here (e.g. agroforestry, pasture cropping) due to reasons set out in the Methods (Section 3.4.1).

Secondly, RA practitioners typically use a holistic and adaptive management philosophy (Briske et al., 2011, Brown, 2018, Gosnell et al., 2019). This can result in prescriptive treatments in scientific studies inadequately reflecting practitioner behaviour (Briske et al., 2008, Briske et al., 2011). Although our analysis provides an important first step to evidencing claims about the benefits of RA, further work to address this knowledge gap could include qualitative studies which give a more holistic overview of RA and observational studies of paired regeneratively and conventionally managed farms, as has been done in the USA (LaCanne and Lundgren, 2018, Rowntree et al., 2020). This could also incorporate other potential benefits of RA, including lowered risk of soil erosion and enhanced soil biodiversity from reducing tillage intensity, decreased nitrogen leaching and therefore water pollution by growing cover crops, and increased soil fertility and control of crop pests and diseases through rotation diversification (Table 3.1).

Finally, the low number of studies which measure both SOC and crop yield for the interventions considered here, and the large heterogeneity within individual studies (Fig A2.2-4), affect the certainty of our results and likely explain the large Credibility Intervals we identified (Table 3.2, Fig A2.6). Increasing the number of studies captured by expanding our systematic review to other climate zones would result in a

larger dataset for analysis and enable the influence of climatic variation on the impacts of RA practices to be determined.

Overall, we do not find evidence to support a win-win between increased soil carbon and crop yield when adopting certain RA practices considered here in temperate oceanic arable systems. Rather, we find increases in SOC concentration, with crop yield remaining relatively unchanged. RA is receiving substantial attention as a climate change mitigation strategy, which requires consideration of the impact of these practices on SOC stocks. Further modelling work finds that if individual practices considered here were implemented across all arable land in Great Britain, this could mitigate 16-27% of current GB agricultural emissions (corresponding to cover crops in every year of an arable rotation, and a four year ley-two year arable rotation, respectively) thus significantly contributing to emissions abatement efforts (Jordon et al., 2022). In contrast, the magnitude of effect we identify for reduced tillage intensity and ley-arable rotations on SOC concentration in our current analysis is low, with Credible Intervals close to zero (Table 3.2), similar to previous meta-analyses (Sanden et al., 2018, Haddaway et al., 2017a, Conant et al., 2017, West and Post, 2002). Although baseline SOC data was a much stronger predictor of endline values than the three management practices considered here (EIBP analysis, Table 3.2), this is unsurprising as there is limited time across the average study duration of 12.5 years for SOC to change substantially in response to management regime, meaning much of the variation in endline SOC is still explained by its initial value.

In addition to soil carbon and crop yield, there are other factors relevant to the climate change mitigation potential of these practices not considered here, which include: i) soil greenhouse gas emissions, for example reduced tillage and cover cropping can increase soil N_2O emissions (Muhammad et al., 2019, Powlson et al., 2014, Basche et al., 2014, Han et al., 2017, Shakoor et al., 2021); 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 RA practices to determine their suitability for inclusion in climate change mitigation strategies, in addition to considering their impact on other soil functions and ecosystem services (Tamburini et al., 2020). If this provides further support for adoption of these interventions, uptake by land managers could be incentivised through policies such as the recently reformed Common Agricultural Policy in the European Union or the new Environmental Land Management schemes in England which seek to enhance environmental outcomes through implementing beneficial management practices on farms.

3.7. Conclusion

We identify that two RA practices – reducing tillage intensity and incorporating leys into rotations – increase soil carbon concentration without negatively impacting crop yield in temperate oceanic arable systems. Maintenance of yields in arable cropping years is likely to appeal to land managers considering adopting these practices.

However, the loss of crop production during the grass-phase of ley-arable rotations is likely to limit 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, currently available evidence does not support a win-win between SOC and yield that some suggest RA can offer in temperate oceanic regions. 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 climate change mitigation potential of RA. Further primary research should investigate the potential synergies and trade-offs between implementing multiple regenerative practices simultaneously by comparing RA with conventional management at a system-scale.

3.8. Acknowledgments

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Chapter 4. Modelling soil carbon stocks following reduced tillage intensity: a framework to estimate decomposition rate constant modifiers for RothC-26.3, demonstrated in north-west Europe

4.1. Summary

This chapter describes a modelling framework that I developed to capture the mechanisms underpinning soil carbon changes following reduced tillage intensity in arable systems. I utilised the process-based soil organic carbon (SOC) turnover model RothC. In particular, I calibrated rate modifiers for the decomposition constants in the model using SOC data from north-west Europe assembled by the systematic review in Chapter 3. The output is a transparent and repeatable framework that is suitable for application in other geographic regions using data generalisable to the context of interest. This chapter provides an important step to meeting the second aim of my thesis in determining the potential for Regenerative Agriculture practices, including reduced tillage intensity, to increase SOC stocks.

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Modelling soil carbon stocks following reduced tillage intensity: a framework to estimate decomposition rate constant modifiers for RothC-26.3, demonstrated in north-west Europe

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4.2. Abstract

Simulating cropland soil carbon changes following a reduction in tillage intensity is necessary to determine the utility of this management practice in climate change mitigation. In instances where reduced or no tillage increases soil carbon stocks, this is typically due to reduced decomposition rates of crop residues. Although some soil carbon models contain *a priori* decomposition rate modifiers to account for tillage regime, these are typically not calibrated to specific climatic regions, and none are currently available for the Rothamsted Carbon Model (RothC). Here, we present a modelling framework to estimate a tillage rate modifier (TRM) for the decomposition rate constants in RothC-26.3 which determine decay between soil carbon pools. We demonstrate this for north-west Europe, using published data assembled through a recent systematic review with propagation of error from input parameters throughout the framework. The small magnitude of soil carbon change following a reduction in

tillage intensity in this region is reflected in our TRM estimates for no-till of 0.95, 95% Credible Intervals [0.91, 1.00], and reduced tillage of 0.93 [0.90, 0.97], relative to conventional high-intensity tillage with a TRM of 1. These TRMs facilitate realistic simulation of soil carbon dynamics following a reduction of tillage intensity using RothC, and our simple, transparent, and repeatable modelling framework is suitable for application in other climatic regions using input data generalisable to the context of interest.

4.3. Introduction

Reducing tillage intensity in arable cropping systems can increase soil organic carbon (SOC) (Sanden et al., 2018, Haddaway et al., 2017, West and Post, 2002). Increased adoption could contribute to land-based climate change mitigation efforts (Bossio et al., 2020, Kämpf et al., 2016, Smith et al., 1998) although the SOC change identified is often small (Jordon et al., 2022b), with redistribution of SOC within the soil profile and a concurrent increase in bulk density resulting in little change in soil carbon stocks (Powlson et al., 2014, Xiao et al., 2020, Angers and Eriksen-Hamel, 2008, Meurer et al., 2018). Determining the potential contribution, or otherwise, of reducing tillage intensity to greenhouse gas mitigation at a regional or territorial level requires modelling approaches that adequately reflect the mechanisms driving soil carbon dynamics.

The principal mechanisms for increases in SOC are higher plant residue inputs (PRI) to soil and reduced rates of decomposition of organic carbon within the soil.

Reduced tillage intensity favours the latter (Senapati et al., 2014, van Groenigen et al., 2011), protecting SOC from degradation through enhanced soil aggregation and reduced soil temperatures (Huang et al., 2018), although simultaneous crop residue retention as part of a conservation agricultural also increases PRI (Lal, 2015). Widely-used and validated soil carbon models tend to simulate equilibrium soil carbon stocks following a change in management through adjusting PRI, with movement of carbon between conceptual pools determined by first-order kinetics (Smith et al., 1997). Decomposition rate constants are routinely adjusted or modified to account for the effect of soil moisture and temperature on decay, and can be amended to account for tillage regime (Jenkinson, 1990, Parton et al., 1988, Bolinder et al., 2012, Gerik et al., 2015, Li et al., 1994).

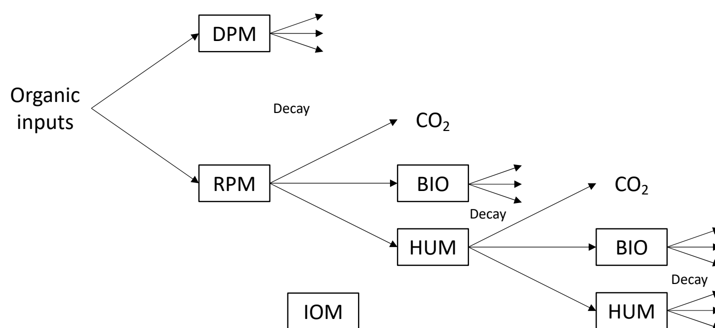

Figure 4.1. Conceptual soil carbon pools in RothC-26.3, after Coleman and Jenkinson (2014). DPM: decomposable plant material, RPM: resistant plant material, BIO: microbial biomass, HUM: humified organic matter, IOM: inert organic matter. Decay of pools determined by first-order kinetics with decomposition rate constant, apart from small inert pool resistant to decomposition.

The Rothamsted Carbon Model (RothC) version 26.3 is a process-based five-compartment model with monthly timesteps (Fig 4.1), developed under temperate agricultural conditions and demonstrated to perform well across climates and biomes

(Smith et al., 1997, FAO, 2019, Jenkinson, 1990, Jenkinson et al., 1999). Advantages of RothC-26.3 include its requirement for few, readily-available, parameters and its ability to run both in 'forward' (estimate change in SOC for known inputs) and 'inverse' (estimate inputs for known change in SOC) modes (Coleman and Jenkinson, 2014). An inverse modelling approach has previously been applied directly to the decomposition rate constants in RothC-26.3 to capture the effects of different tillage intensities (Rampazzo Todorovic et al., 2014), although this approach risks overfitting model parameters to the data. Alternatively, the decomposition rate constants could be multiplied by a single tillage rate modifier (TRM) based on tillage intensity. Soja et al. (2010) calibrated such TRMs in RothC to account for different tillage practices in Austrian vineyards, and rate modifier terms have also been developed to better capture SOC dynamics in saline soils (Setia et al., 2011), and aluminium-rich and paddy soils (Yokozawa et al., 2010). Further, generalisable estimates for RothC input parameters have previously been calculated using data from multiple study sites (Falloon et al., 1998).

Here, we present a modelling framework to estimate tillage rate modifiers for 'reduced tillage' and 'no tillage' practices on arable farmland, to be used as multipliers for the decomposition rate constants in RothC-26.3. We demonstrate this approach for north-west Europe, using SOC data from studies of tillage intensity in temperate oceanic regions identified by a recent systematic review (Jordon et al., 2022b). The TRM estimates presented here are appropriate for use in north-west Europe and have been applied in other work to simulate adoption of no and reduced

tillage practice across arable land in Great Britain (Jordon et al., 2022a). Further, our framework is intended to be applicable in other regions using data appropriately generalisable to the context of interest.

4.4. Methods

Jordon et al. (2022b) identified 19 studies that measured soil organic carbon (and crop yield) under differing arable tillage intensity regimes in regions of north-west Europe with a temperate oceanic climate (Köppen-Geiger classification Cfb (Peel et al., 2007)). Studies identified were conducted in the UK, France, Belgium, Germany, the Netherlands, Denmark and Spain. From this, we extracted 23 paired observations of soil carbon under conventional tillage (CT) vs no-till (NT) treatments (12 studies), and 20 observations under CT vs reduced tillage (RT) treatments (14 studies), available online (Jordon, 2022). We selected paired observations where the only difference between study treatments was tillage regime, such that where studies applied tillage treatments factorially with other treatments, paired observations were extracted for each level of the factor(s) not of interest. Where studies presented observations for CT, RT and NT treatments, they were included both in the CT-NT and CT-RT analyses.

RothC-26.3 was implemented in R version 4.0.3 using the *RothCModel* function in the package *SoilR* (Sierra et al., 2012, R Core Team, 2020), which allows plant residue input (PRI), soil carbon pool sizes, and decomposition rates to be explicitly specified. We ran our model framework for each study site, using site-specific input

parameters from global databases extracted using site coordinates where required parameters were not provided in article texts or available on request from the corresponding author (Table 4.1).

Table 4.1. Input parameters for RothC-26.3 in our model framework. Global spatial data are at 1km resolution, and were extracted for each study site using degree decimal coordinates

Model parameter	Source	Citation
Soil organic carbon (g.100g^{-1})	Studies in systematic review database	(Jordon et al., 2022b)
Soil clay content (%)	WISE30sec*	(Batjes, 2016)
Soil bulk density (g.cm^{-3})†		
Mean monthly air temperature (ºC)††	TerraClimate	(Abatzoglou et al., 2018)
Mean monthly precipitation (mm)		
Potential evapotranspiration (mm)		

* where not presented in study
† Soil bulk density was required to convert soil carbon data from concentration (g.100g^{-1}) to stocks (t.ha^{-1}) in order to input to RothC
†† TerraClimate only provides monthly minimum and maximum temperatures, so we approximated monthly mean temperature by averaging the minimum and maximum

We propagated error through our model framework using standard deviations associated with inputs to generate normally distributed random samples of parameters for 100 model iterations per observation. Where clay and bulk density estimates were given in study articles, their respective standard deviations were assumed to be zero, such that error is only propagated for WISE30sec values to capture their estimation uncertainty. To derive standard deviations for the required climatology data, we downloaded monthly averages for each year in the period 1981-2010 and calculated the mean and standard deviation across these 30 years. Some studies included in the systematic review database assembled by Jordon et al. (2022b) do not present error terms for SOC estimates. Since discarding incomplete data can bias model estimates (Weir et al., 2018), we used multiple imputation

methods to generate estimates for missing values, which explicitly represents the uncertainty associated with imputation in the model output (Lajeunesse, 2013). We used the *mice* package in R to generate ten imputed datasets (van Buuren and Groothuis-Oudshoorn, 2011) and drew ten random samples using the imputed values from each dataset to generate the 100 samples required.

Table 4.2. Modelling framework used to estimate tillage rate modifiers (TRM), parametrised with paired observations of conventional tillage (CT) with no-till (NT) or reduced tillage (RT). PRI: plant residue input.

Stage	SOC input†	Output	Model run time	Initial soil carbon pools	Plant residue input	Decomposition rate constants	Assumptions
1. Inverse model PRI for CT endline	CT endline	CT endline PRI	1000 years	0‡	*Inverse modelled*	Model defaults	CT SOC is at equilibrium at study endline
2. Spin up NT/RT baseline SOC pool sizes	*na*	NT/RT baseline SOC pool sizes	1000 years	0‡	CT endline PRI **(1)**	Model defaults	NT/RT baseline SOC is at equilibrium; PRI is same as CT treatment
3. Inverse model decomposition rate modifier for NT/RT treatment	NT/RT endline	NT/RT rate modifier	Study years	NT/RT baseline SOC pool sizes **(2)**	CT endline PRI **(1)**	Model defaults multiplied by single rate modifier	PRI is same as CT treatment

† used in inverse modelling stage
‡ Inert organic matter (IOM) pool estimated as $IOM = 0.049(SOC^{1.139})$ following Falloon et al. (1998), where SOC is the soil organic carbon stock (t.ha^{-1})

Our modelling framework and assumptions are presented in Table 4.2 and the full R code we used is provided online (Jordon, 2022). Inverse modelling was conducting via a linear optimisation process using the optim function with Brent method in base R (R Core Team, 2020). We used CT ‘endline’ SOC (i.e. most recent measurement in study) to inverse model PRI. We assumed PRI to be the same within each CT-NT/RT paired observation due to the only difference between study treatment management being tillage regime. Although crop residue retention alongside reduced tillage intensity in conservation agriculture may increase PRI, our pairing of study treatments ensured similar crop residue fate between treatments, i.e. both

removed/burnt, or incorporated in CT/RT and left on surface in NT. Further, if reduced tillage intensity (RT or NT) resulted in higher crop Net Primary Productivity (NPP) compared to CT, this would likely increase PRI (Bolinder et al., 2007). However, meta-analysis of the yield data from the study treatments used here found no difference in crop yield (Jordon et al., 2022b) (found to relate to NPP (Bolinder et al., 2007)) between tillage treatments, in agreement with the findings for this region from another recent meta-analysis (Sun et al., 2020). This allowed us to inverse model TRMs for the RothC decomposition rate constants for NT and RT endline SOC values by keeping the PRI constant. Our approach assumes a TRM of 1 for conventional tillage, because the decomposition rate constants in RothC were originally calibrated in arable systems with cultivation.

We used the *brms* package to fit a Bayesian intercept-only model to estimate the average tillage rate modifier across all paired observations (Bürkner, 2018). Due to the large amount of data with missing errors imputed for use in our model framework we generated three estimates to test the sensitivity of the results to different data availability and quality:

1. Errors present (EP)
2. Errors imputed where missing (EI)
3. Critical appraisal (EIHV): as in (2), but only observations that have high validity based on level of spatial replication and experimental design (see Jordon et al. (2022b) for details)

4.5. Results and Discussion

We present a simple, transparent, and repeatable framework for estimating TRMs to uniformly adjust the decomposition rate constants in RothC-26.3. We demonstrate our approach using data from north-west Europe, identifying a TRM for no-tillage in the range 0.95 [0.91, 1.00] to 1.02 [0.97, 1.07] and for reduced tillage between 0.93 [0.90, 0.97] and 0.99 [0.95, 1.03] (Table 4.3). Of these, only the reduced tillage TRM from the EI analysis has 95% Credible Intervals not overlapping with 1 so is significantly different from the rate of decomposition under conventional tillage. This is unsurprising given meta-analysis of the data used here identified only a very small increase in SOC *concentration* following adoption of reduced or no tillage in temperate oceanic regions (Jordon et al., 2022b), without accounting for any concurrent increase in bulk density which can result in little or no change in soil carbon *stocks* on an equivalent soil mass basis (Powlson et al., 2014, Meurer et al., 2018). Nevertheless, our TRM estimates give realistic soil carbon dynamics following a change in management (i.e. modest increase with plateauing dynamic (Smith, 2014)) when used in RothC to simulate equilibrium soil carbon stocks following adoption of no- or reduced-tillage (Fig 4.2). Further, our framework is applicable to data from other regions where reduction of tillage has a greater influence on SOC (Sun et al., 2020, West and Post, 2002), which we would expect to result in larger TRMs.

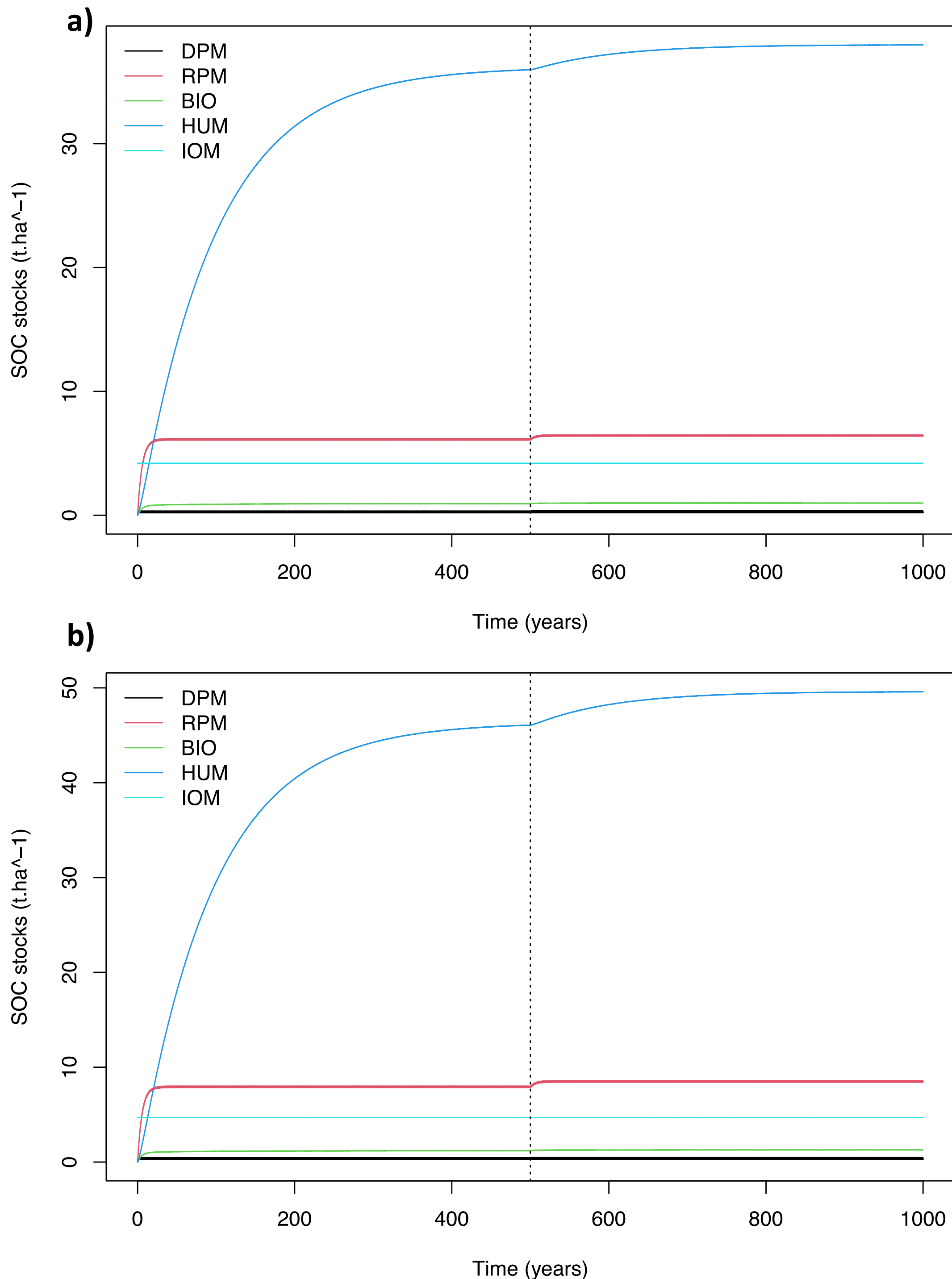

Figure 4.2. RothC soil carbon pool dynamics, initialised for 500 years using conventional tillage (CT) plant residue input (PRI) from dataset, followed by simulated reduction of tillage intensity using tillage rate modifier (TRM) from year 500 (dashed vertical line). All parameters are mean values from implementation of respective modelling framework. **(a)** No-till: CT PRI 2.68 $t.ha^{-1}.month^{-1}$, TRM 0.95, SOC_{500} 47.4 $t.ha^{-1}$, SOC_{1000} 49.8 $t.ha^{-1}$. **(b)** Reduced tillage: CT PRI 3.52 $t.ha^{-1}.month^{-1}$, TRM 0.93, SOC_{500} 60.2 $t.ha^{-1}$, SOC_{1000} 64.4 $t.ha^{-1}$. DPM: decomposable plant material, RPM: resistant plant material, BIO: microbial biomass, HUM: humified organic matter, IOM: inert organic matter. Figure after Sierra (2015).

Table 4.3. Tillage rate modifier (TRM) estimates for no-till (NT) and reduced tillage (RT) with 95% Credible Intervals in square brackets. * denotes where not overlapping with 1.

	No tillage			Reduced tillage		
	NT TRM	Observations	Studies	RT TRM	Observations	Studies
Error present (EP)	1.02 [0.97, 1.07]	16	6	0.93 [0.75, 1.09]	12	6
Error imputed (EI)	0.95 [0.91, 1.00]	23	12	0.93 [0.90, 0.97]*	20	14
Error imputed, high validity (EIHV)	1.02 [0.97, 1.07]	18	8	0.99 [0.95, 1.03]	14	8

Other models generally assume a larger effect of tillage on the rate of decomposition of soil carbon pools[1]. For example, the Century model multiplies decomposition rates by up to 1.6 (Metherell et al., 1993), the Environmental Policy Integrated Climate (EPIC) model applies an exponent coefficient in the range 5-15 (Gerik et al., 2015), the DeNitrification-DeComposition (DNDC) model increases rates by 1.5 times for disk cultivation and by 3 times for ploughing (Li et al., 1994), and an optimised rate modifier of 1.2 has been used in the Integrated Carbon Balance Model (ICBM) for rotations with more frequent tillage (Bolinder et al., 2012). Other approaches include increasing the proportion of net primary productivity retained as crop residues, from 35% for conventional tillage to 55% for conservation tillage as in SOCRATES (Grace et al., 2006). Although these higher adjustments have been found to perform well, this could be due in part to their development using datasets from different climates or cropping systems to our demonstration region, and underlying differences

[1] Most models increase tillage rate modifiers to account for higher tillage intensity rather than decrease to account for reduced tillage intensity as in our approach.

between models in their core decomposition rate constants. Where future research uses data from warmer or drier climates to parametrise our framework, this may result in a greater magnitude of TRM than we identify here (Sun et al., 2020). Although some syntheses have found little influence of temperature or rainfall (Luo et al., 2010), or climate zone (Haddaway et al., 2017), on SOC changes under different tillage regimes, this could be due to their focus on predominantly temperate regions.

Key advantages of our approach include the use of a systematic review database to parametrise our modelling and ability to propagate error from the underlying studies. However, our results are sensitive to which, and how many, observations are used to estimate TRMs, with a trend towards a greater magnitude of TRM when more observations are included (Table 4.3). This highlights the issue of data completeness when attempting to derive model parameters from published studies; six NT studies and eight RT studies in our dataset did not present error terms for SOC measurements, necessitating multiple imputation methods for inclusion. Further, it would be more mechanistically accurate to initialise baseline (i.e. pre-intervention) soil carbon pools for the CT and NT/RT treatments using baseline SOC measurements, to enable PRI to be estimated for the study duration rather than over a 1000-year spin-up. This was not possible as 13 CT-NT observations and 12 CT-RT observations did not present baseline data. We were unable to use imputed baseline values as this led to a modelling artefact where it appeared that SOC greatly increased in the CT treatments, resulting in unrealistically high estimates of study PRI which led to incorrect dynamics of increased decomposition in NT and RT

treatments in order to match study SOC measurements. Where sufficient baseline SOC data is available in future work, this should be incorporated when implementing our framework. Although we feel that assuming PRI is constant within each CT-NT/RT paired observation is reasonable here due to the reasons outlined in the Methods, in instances where PRI is anticipated to differ due to differences in crop residue management or known changes in crop yield, a modified approach would be required to implement our framework. Identifying the effect of reduced tillage intensity vs crop residue retention *via* an inverse modelling approach would require a dataset with factorial treatments of tillage intensity and straw retention to establish the PRI increase from straw retention, tillage rate modifier from reduced tillage intensity, and any interaction between these. Further, where differences in crop yield between tillage regimes are known to exist, a method similar to that described by Bolinder et al. (2007) could be implemented to estimate a proportional tillage factor for *PRI* using crop yield data, thus accounting for this effect in an additional step between stages 2 and 3 in our framework (Table 4.2).

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Chapter 5. Can Regenerative Agriculture increase national soil carbon stocks? Simulated country-scale adoption of reduced tillage, cover cropping, and ley-arable integration using RothC

5.1. Summary

This chapter meets the second aim of my thesis by simulating the potential total change in SOC stocks across arable land in Great Britain (GB) if three different Regenerative Agriculture practices were adopted; reduced tillage, cover cropping, and ley-arable integration. I achieved this using the soil organic carbon (SOC) data assembled by systematic review in Chapter 3 and the modelling approach I developed in Chapter 4. I found that if 61,413 km^2 of GB arable land was planted with cover crops in every year of an arable rotation, and if a rotation of four years ley – two years arable cropping was implemented, respectively, this could increase SOC stocks over 30 years equivalent to 16-27% of current emissions from GB agriculture thus significantly contributing to emissions abatement efforts.

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Can Regenerative Agriculture increase national soil carbon stocks? Simulated country-scale adoption of reduced tillage, cover cropping, and ley-arable integration using RothC

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5.2. Abstract

Adopting Regenerative Agriculture (RA) practices on temperate arable land can increase soil organic carbon (SOC) concentration without reducing crop yields. RA is therefore receiving much attention as a climate change mitigation strategy. However, estimating the potential change in national soil carbon stocks following adoption of RA practices is required to determine its suitability for this. Here, we use a well-validated model of soil carbon turnover (RothC) to simulate adoption of three regenerative practices (cover cropping, reduced tillage intensity and incorporation of a grass-based ley phase into arable rotations) across arable land in Great Britain (GB). We develop a modelling framework which calibrates RothC using studies of

these measures from a recent systematic review, estimating the proportional increase in carbon inputs to the soil compared to conventional practice, before simulating adoption across GB. We find that cover cropping would on average increase SOC stocks by 10 $t.ha^{-1}$ within 30 years of adoption across GB, potentially sequestering 6.5 megatonnes of carbon dioxide per year ($MtCO_2.y^{-1}$). Ley-arable systems could increase SOC stocks by 3 or 16 $t.ha^{-1}$, potentially providing 2.2. or 10.6 $MtCO_2.y^{-1}$ of sequestration over 30 years, depending on the length of the ley-phase (one and four years, respectively, in these scenarios). In contrast, our modelling approach finds little change in soil carbon stocks when practising reduced tillage intensity. Our results indicate that adopting RA practices could make a meaningful contribution to GB agriculture reaching net zero greenhouse gas emissions despite practical constraints to their uptake.

5.3. Introduction

Increasing terrestrial carbon sequestration is currently of global interest in efforts to mitigate anthropogenic greenhouse gas (GHG) emissions (IPCC, 2019). It has been demonstrated that there is substantial potential to increase soil carbon stocks on agricultural land (Griscom et al., 2017, Bossio et al., 2020, Kampf et al., 2016, Lal, 2004); a preferred setting since use for food production can continue, in contrast to interventions on natural and semi-natural habitats which can compromise biodiversity and ecosystem service delivery (Veldman, 2019, Veldman et al., 2015). Building soil organic carbon (SOC) through changes in agricultural land management practices is also important in mitigating widespread and costly soil degradation

(Graves et al., 2015, Prout et al., 2020), thus safeguarding crop yields and promoting other ecosystem services such as water flow regulation and nutrient retention (Bradford et al., 2019, Smith et al., 2021). However, limitations of soil carbon sequestration for climate change mitigation include sink saturation, non-permanence following discontinuation of beneficial management, risk of displacement of emissions through compensatory cultivation elsewhere, and difficulties in verifying sequestration (Smith, 2012).

The Regenerative Agriculture (RA) paradigm is receiving increasing attention from land managers and policy makers due to its proposed ability to simultaneously contribute to climate change mitigation and ameliorate degraded soils by sequestering SOC through changes in management practices (Moyer et al., 2020, Newton et al., 2020, Giller et al., 2021). Although multiple definitions exist, RA can best be defined as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services” (Schreefel et al., 2020).

A recent meta-analysis of RA practices in temperate regions demonstrated the potential to increase soil carbon concentration without any yield reduction in cropping years through reducing tillage intensity and incorporating a ley-phase into arable rotations (Jordon et al., 2022). However, evaluating the potential contribution of RA to climate change mitigation requires regional-scale simulation of the total potential change in soil carbon stocks following adoption.

Models of soil carbon turnover enable simulation of the effect of changes in land management on SOC stocks, while accounting for regional variation in climate and soils. The Rothamsted carbon model (RothC) version 26.3 is a process-based five-compartment model (Fig 4.1) with monthly timesteps, developed under temperate agricultural conditions and validated across climates and biomes (Smith et al., 1997b, FAO, 2019, Jenkinson, 1990, Jenkinson et al., 1999, Falloon and Smith, 2002). Advantages of RothC include its requirement for few, readily-available, parameters and its ability to run both in ‘forward’ (estimate change in SOC for known inputs) and ‘inverse’ (estimate inputs for known change in SOC) modes (Coleman and Jenkinson, 2014). Previous approaches to simulating the effects of land management changes on soil carbon include extrapolating an observed SOC change over a larger area (King et al., 2004, Smith et al., 2000b), *a priori* adjusting model input parameters in an effort to best represent management practices (Smith et al., 2005, Lugato et al., 2014), deriving soil carbon trends using data from long-term experiments (Smith et al., 1997a) or using average values from a meta-analysis of published literature (Poeplau and Don, 2015). However, more exact estimates of soil carbon changes can be generated by combining inverse and forward runs of a process-based model such as RothC, publicly available spatial datasets of required climatology and soil inputs, and empirical SOC measurements from published studies. This enables both the model calibration, using real-world data, and simulation stages to be based on site-specific inputs. Mirroring real-world dynamics as closely as possible in soil carbon modelling is important to prevent the

contribution of land management changes to climate change mitigation from being overstated.

Here, we develop a modelling framework using RothC to estimate the total change in soil carbon stocks if three constituent practices of RA were adopted at a country-scale for Great Britain (England, Scotland and Wales, not including Northern Ireland). We use published SOC data obtained from studies of reduced tillage intensity, cover cropping and incorporation of grass-based leys into arable rotations conducted in temperate oceanic regions assembled by Jordon et al. (2022), to maximise generalisability to the context of interest. We aimed to evaluate the extent to which increased adoption of RA practices on temperate arable land can sequester carbon to mitigate GHG emissions.

5.4. Methods

Changes in soil carbon are usually driven by one or a combination of changes in i) carbon entering the soil, most of which will be from plant residue inputs (PRI), or ii) the rate of decomposition of carbon pools within the soil. Cover cropping and ley-arable adoption affect SOC primarily *via* the former mechanism, while reducing tillage intensity favours the latter. Our framework comprised two stages: i) estimating the change in either PRI (following adoption of cover cropping or ley-arable rotations) or rate of SOC decomposition (following reduced tillage intensity) in the studies assembled by Jordon et al. (2022) then ii) using the resulting distributions of PRIs or

tillage rate modifiers (TRMs) to simulate adoption of these practices at a 1 km resolution for arable land in Great Britain (GB).

RothC-26.3 was implemented in R version 4.0.3 using the *RothCModel* function in the package *SoilR* (Sierra et al., 2012, R Core Team, 2020). This function allows PRI, soil carbon pool sizes, and decomposition rates to be specified by the user. Inverse modelling steps (detailed below) were conducting *via* a linear optimisation process using the *optim* function with Brent method in base R (R Core Team, 2020). The R code and supporting data developed for and used here to implement our framework is publicly available online (Jordon, 2021).

5.4.1. Model calibration

To estimate the change in PRI following adoption of cover crops and ley-arable, we implemented the first stage of our model framework for all treatments from each relevant study identified by Jordon et al. (2022). First, we used the baseline (i.e. pre-intervention) SOC stock reported in the study (assumed to be at equilibrium) to inverse model the PRI before the study began, using study-site-specific input parameters in RothC (Table 5.1). This PRI was used to initialise or 'spin-up' the conceptual pools of soil carbon (Fig 4.1), by running RothC in 'forward' mode for 1000 years, which when summed corresponds to the baseline SOC stock. Subsequently, we used these initial pool sizes to run RothC in 'inverse' mode for the duration of the study in years, to estimate the PRI which resulted in the endline (i.e. last available) SOC measurement for that treatment.

Table 5.1. Sources of input data used to parametrise RothC-26.3 for calibration of our modelling framework and Great Britain simulation, for three Regenerative Agriculture practices. All parameters we extracted from the WISE30sec and TerraClimate datasets are available online (Jordon, 2021, Jordon, 2022b).

Model parameter[1]	Model calibration	Great Britain simulation
Soil organic carbon (g.100g^{-1})	Jordon et al. (2022)	WISE30sec[4] (Batjes, 2016), 1 km resolution harmonised to the CEH land cover map (Rowland et al., 2017)
Soil clay content (%)	If not presented in original study, extracted from WISE30sec[4] (Batjes, 2016) using study site coordinates	
Soil bulk density (g.cm^{-3})[2]		
Mean monthly air temperature (°C)[3]	Extracted from TerraClimate (Abatzoglou et al., 2018) using study site coordinates	TerraClimate (Abatzoglou et al., 2018), 1 km resolution harmonised to the CEH land cover map (Rowland et al., 2017)
Mean monthly precipitation (mm)		
Potential evapotranspiration (mm)		

[1] Although other 1 km^2 resolution databases exist for soil carbon modelling in the United Kingdom (UK) (Falloon et al., 2006, Bradley et al., 2005), these use the proprietary LandIS National Soil Map data products, so here we developed an alternative approach using publicly available global datasets.
[2] Soil bulk density was required to convert soil carbon data from concentration (g.100g^{-1}) to stocks (t.ha^{-1}) in order to input to RothC
[3] TerraClimate only provides monthly minimum and maximum temperatures, so we approximated monthly mean temperature by summing the minimum and maximum and dividing by two.
[4] WISE30sec data are available for sampling depths of 0-20cm and 20-40cm. We therefore took a weighted average of these to generate data for 0-30cm sampling depth.

To propagate deterministic uncertainty (error already present in input data) through our modelling, we ran 100 model iterations per study treatment, using standard deviations associated with inputs to generate normally distributed random samples of parameters. These distributions were created using the *rnorm* function in base R (R Core Team, 2020), or the *truncnorm* function (Mersmann et al., 2018) bounded between zero and infinity, where negative values for those parameters are not possible (e.g. precipitation). Where clay and bulk density measurements were presented in studies, these were assumed to have standard deviations of zero, in order that error was only propagated for WISE30sec values (Batjes, 2016) to capture the uncertainty inherent in using these estimates rather than site-specific measurements. To derive standard deviations for the required climatology data

(Table 5.1), we downloaded monthly averages for each year in the period 1981-2010 and calculated the mean and standard deviation across these 30 years.

Table 5.2. Proportional change in Plant Residue Input (PRI) following adoption of cover cropping or ley-arable systems, calibrated using a systematic review dataset assembled by Jordon et al. (2022). Results are given for different levels of data inclusion based on input data availability and quality (see text for details), with standard deviation of means given in brackets. R code used to calculate the proportional changes in PRI is available online (Jordon, 2021).

Intervention	**Management change**	**Data included in analysis**	**Proportional change in PRI** *mean (standard deviation)*	**n**[1] *Obs*	*Studies*
Cover crops	Cover crops present in all years of rotation (proportion present of 1) rather than no years (proportion of 0).	BPEP	2.09 (0.0840)	32	3
		BPEI	1.03 (0.0355)	51	6
		BIEI	1.69 (0.0432)	79	12
		CA[2]	1.56 (0.0450)	61	8
Ley-arable	**L1A2**: One year ley-phase followed by two years arable rather than continuous cropping	BPEP	-0.446 (18.3)	14	2
		BPEI	1.33 (0.0434)	31	5
		BIEI	1.37 (0.0225)	68	14
		CA[3]	1.19 (0.0143)	49	10
	L4A2: Four-year ley-phase followed by two years arable rather than continuous cropping	BPEP	1.18 (0.0572)	14	2
		BPEI	1.384 (0.0544)	31	5
		BIEI	2.62 (0.127)	68	14
		CA[3]	1.92 (0.0865)	49	10

[1] The number of observations (n) corresponds to the total number of treatments across all relevant studies, also given, that the model framework was run for.
[2] Of 61 observations in this dataset, 24 were complete (baseline SOC and error present), 18 had baseline SOC imputed (30%), and 37 had errors imputed (61%).
[3] Of 49 observations in this dataset, 6 were complete (baseline SOC and error present), 26 had baseline SOC imputed (53%), and 43 had errors imputed (88%).

Some studies included in the database assembled by Jordon et al. (2022) do not present error terms for SOC estimates or baseline SOC measurements. Because discarding incomplete data can bias model estimates (Weir et al., 2018), we used multiple imputation methods to generate estimates for missing values, which has the advantage of explicitly representing the uncertainty associated with imputation in the model output (Lajeunesse, 2013). We imputed 30% and 53% of baseline SOC values, and 61% and 88% of error values, for the data used to estimate proportional changes in PRI following adoption of cover crops and ley-arable systems,

respectively (Table 5.2). We used the *mice* package in R to generate ten imputed datasets (van Buuren and Groothuis-Oudshoorn, 2011) and extracted ten random samples using the imputed values from each of these datasets to arrive at the 100 samples per observation required.

Jordon et al. (2022) present cover cropping and ley-arable treatments as continuous variables in their dataset, with cover cropping expressed as a proportion of the rotation that cover crops are present (zero to one), and ley-arable as the duration of the ley-phase in the rotation (one to six years). We pooled endline PRI estimates across all treatments from all relevant studies (100 iterations per observation to allow propagation of error) and used the *brms* package to fit a Bayesian model to this data (Bürkner, 2018), with endline PRI as the response variable and a weakly informative normal prior distribution (mean 0, standard deviation 1). For cover cropping, cover crop proportion was the sole explanatory variable, but for ley-arable studies both ley and arable durations (years) within the treatment rotation were included as explanatory variables to allow two rotation types to be simulated: a three-year rotation with one year ley and two years arable (L1A2), and a six-year rotation with four years ley and two years arable (L4A2). We then extracted samples from the posterior distribution to calculate the proportional change in PRI if cover cropping or two ley-arable rotations were adopted, relative to 1 which represents ‘conventional’ practice with no cover crops or ley-phase. We do not explicitly represent different cover crop or ley compositions in our scenarios and therefore differences in quality of organic matter inputs which could influence the rate of decomposition (e.g. through

the presence/absence of legumes). However, standard deviations of the proportional changes in PRI are used to capture variability in practices between study treatments used to calibrate our framework and are propagated through the GB simulation, reflecting plausible diversity in practices if adopted in real-world conditions.

Due to our use of imputation for data with missing errors and/or baseline SOC for inclusion in our model framework we generated four estimates to test the sensitivity of the results to different data availability and quality (Table 5.2):

4. Baseline SOC present, errors present (BPEP)
5. Baseline SOC present, missing errors imputed (BPEI)
6. Baseline SOC imputed and/or missing errors imputed (BIEI)
7. Critical appraisal (CA): as in (3), but only observations that have high validity based on level of spatial replication and experimental design included (see Jordon et al. (2022) for details)

Note that for (1-3) endline SOC data is always present. We used the values generated from approach (4) in our GB simulation as a best compromise between input data quantity and quality (see footnotes of Table 5.2 for level of data imputation used to generate these estimates).

A similar approach was developed by (Jordon and Smith, 2022) who estimated TRMs for adjusting the decomposition rate constants in RothC to account for reduced tillage intensity using the same dataset from Jordon et al. (2022). Here, we use their TRM estimates of 0.99 (Standard Deviation 0.02) for reduced tillage, and

1.02 (SD 0.03) for no-tillage, relative to 1 (i.e. default decomposition rate constants) for conventional full-inversion tillage (Jordon, 2022a).

5.4.2. Great Britain simulation

We used the UK Centre for Ecology & Hydrology (CEH) land cover map 1 km dominant target class raster (Rowland et al., 2017) to identify 1 km^2 pixels of GB which are predominantly arable (i.e. more than 50% of land cover within that pixel classified as arable). We assumed no current adoption of reduced tillage intensity, cover cropping or ley integration in GB arable rotations, which, although clearly erroneous, we considered appropriate as we were seeking to indicate the relative magnitude of SOC stock change by transitioning from no to complete adoption of these practices, rather than quantify the current unfulfilled potential for this in GB. Because RothC is not suitable for use with organic or organo-mineral soils (Falloon et al., 2006), we excluded 92 pixels with a WISE30sec SOC concentration above 100 $g.kg^{-1}$, and a further 389 pixels with artefact SOC concentrations below 0 $g.kg^{-1}$, resulting in 61,413 1 km^2 pixels for inclusion in our spatially-explicit simulation. RothC was unable to run for some of these pixels due to unreasonable input parameters; we give the number of pixels successfully run (n) for each intervention in Table 5.3. We anticipate these issues with the input data are due to limitations of the taxotransfer scheme applied in WISE30sec (Batjes, 2016). However, use of alternative proprietary data products such as the LandIS National Soil Map would potentially limit the reproducibility of our work and preliminary studies with soil models show little difference in simulated SOC change in GB when using either the

Harmonised World Soil Database (precursor to WISE30sec) or LandIS Soil Map as model inputs (Smith, P. pers comm.). We assumed that using the dominant target class raster provided a good proxy of all arable land through non-arable land area within these squares being approximately matched by arable land in other squares with a different dominant target class. However, 61,413 1 km^2 pixels implies a total GB arable area of 6,141,300 ha, whereas the area of arable crops in the June 2021 census was 4,339,000 ha (Defra, 2021). Therefore, we weighted the estimates of total soil carbon sequestration and GHG mitigation in Table 5.3 to reflect this actual arable area (Table S1, available with online version of article).

Table 5.3. Impact of adopting three Regenerative Agriculture practices across all arable land in Great Britain (4,339,000 ha) on total soil carbon stocks (Megatonnes, Mt) to 30cm depth. The total difference in SOC stocks from the baseline after 30 years (corresponding to the year 2050) and when a new equilibrium is reached are also given, along with the total and rate of carbon sequestration possible ($MtCO_2$) for the first 30 years after implementation[1]. Values given in brackets are estimate standard deviations.

Intervention	Baseline[2]	30 years				Equilibrium		n[3]
	Mt C	Mt C	Δ Mt C	Δ $MtCO_2$	$MtCO_2.y^{-1}$	Mt C	Δ Mt C	
Reduced tillage	261 (0.0720)	262 (0.0721)	0.904 (0.102)	3.31 (0.373)	0.110 (0.0124)	263 (0.0725)	2.48 (0.102)	61,372
No tillage		259 (0.0713)	-1.91 (0.101)	-7.01 (0.371)	-0.234 (0.0124)	256 (0.0707)	-4.48 (0.100)	
Cover crops		314 (0.0865)	53.1 (0.113)	194 (0.412)	6.48 (0.0137)	394 (0.108)	133 (0.130)	61,374
L1A2		279 (0.0768)	17.9 (0.105)	65.7 (0.386)	2.19 (0.129)	306 (0.0841)	45.1 (0.111)	61,381
L4A2		348 (0.0960)	87.2 (0.120)	319 (0.440)	10.6 (0.147)	479 (0.132)	218 (0.150)	

[1] We do not present carbon dioxide equivalents for the total change in SOC once a new equilibrium is reached, because this would occur after 100+ years so be less relevant for climate change mitigation targets. We also do not present a per annum rate of change because the soil carbon dynamics are non-linear as they approach equilibrium.
[2] We ran separate simulations for each intervention which resulted in different estimates of total baseline soil carbon stock (Table S1, see online article). However, at this level of precision total baseline SOC is the same across all intervention simulations.
[3] Number of 1 km^2 pixels that our RothC modelling framework ran for each intervention.

We used WISE30sec SOC concentration ($g.kg^{-1}$) and soil bulk density ($g.cm^{-3}$) values to calculate SOC stocks ($t.ha^{-1}$) for 30 cm soil sampling depth at each pixel, which we assumed to be at equilibrium. We ran RothC in inverse mode using spatially explicit inputs (Table 5.1) to estimate the current PRI for each pixel. We then proportionally adjusted this site-specific PRI by the CA values in Table 5.2 to simulate adoption of cover cropping (present every year in arable rotation) or two ley-arable rotations (L1A2 and L4A2). A proportional adjustment rather than absolute increase was used to account for the inherent differences in Net Primary Productivity and therefore magnitude of PRI increase possible based on site pedological and climatic conditions, after Smith et al. (2005). To simulate reduced or no tillage, we assumed PRI remained constant and multiplied the default decomposition rate constants in RothC by the TRMs of 0.99 and 1.02, respectively (Jordon and Smith, 2022). We executed this forward run for two time horizons: i) 30 years, to estimate the potential change in carbon stocks by the year 2050 which could contribute to national net zero emissions targets (Climate Change Committee, 2019), and ii) 1000 years, to estimate the total soil carbon change once this has reached a new equilibrium. We used the same method to propagate deterministic error as in the model calibration step, with 100 modelling iterations per pixel. We simulated interventions implemented in isolation rather than in combination because most studies used to parametrise our framework consider single interventions, preventing us from determining potential interactions in their effect on soil carbon. We ran the model in parallel for multiple pixels simultaneously using the *foreach* package

(Microsoft and Weston, 2020), implemented on the University of Oxford's Advanced Research Computing facility (Richards, 2015)

We calculated the SOC stock at baseline, 30 years, and equilibrium (mean and standard deviation) from the 100 model iterations for each 1 km^2 pixel. We estimated mean and 95% Credible Intervals for average SOC stocks under each intervention by conducting an intercept-only analysis of pixel means that accounted for their standard error using the *brms* package (Bürkner, 2018). To estimate the total carbon sequestration and therefore carbon dioxide (CO_2) emissions abatement possible across all GB arable land (Table 5.3), we summed the mean SOC stock across all 1 km^2 arable pixels and weighted this by the actual area of GB arable land (Table S1, available with online version of article). To calculate the standard deviation of these summed mean values, we assumed that pixels were independent of each other such that the variance of the sum equals the sum of variances. This is likely to be an underestimate because adjacent pixels are not independent (due to similarity in input parameters) and therefore have positive covariance. However, we feel this is a necessary approximation given the difficulty of calculating a covariance matrix for the large number of pixels summed here. We plotted the results of our simulations using the *ggplot* and *raster* packages (Hijmans, 2021, Wickham, 2016, FC and Davis, 2021). To decompose the sources of variation in our outputs, we fit linear models using the *lm* function (R Core Team, 2020) that contained different combinations of model input parameter distributions, and plotted the adjusted R^2 as a measure of the

variation in the output explained by different inputs. All R code is available online (Jordon, 2021).

5.5. Results and Discussion

5.5.1. Changes in SOC stocks

We demonstrate substantial increases in soil organic carbon (SOC) stocks across Great Britain (GB) are possible if Regenerative Agriculture (RA) practices are adopted on arable land in an illustrative temperate region. Growing over-winter cover crops in every year of an arable rotation has the potential to increase cropland SOC stocks in GB by an average of 20.3% after 30 years, compared with no cover cropping (Fig 5.1). Including grass-based leys in an arable rotation with low frequency (one year ley followed by two years arable, L1A2) increases SOC stocks by 6.9%, or 33.4% if at high frequency (four years ley followed by two years arable, L4A2) within 30 years compared with continuous arable cropping (Fig 5.1). We identify less potential for reducing tillage intensity to affect SOC stocks, with an average increase of 0.36% over 30 years when reduced tillage is adopted, and a decrease of 0.72% when no till is implemented, compared to conventional full-inversion tillage (Fig 5.1).

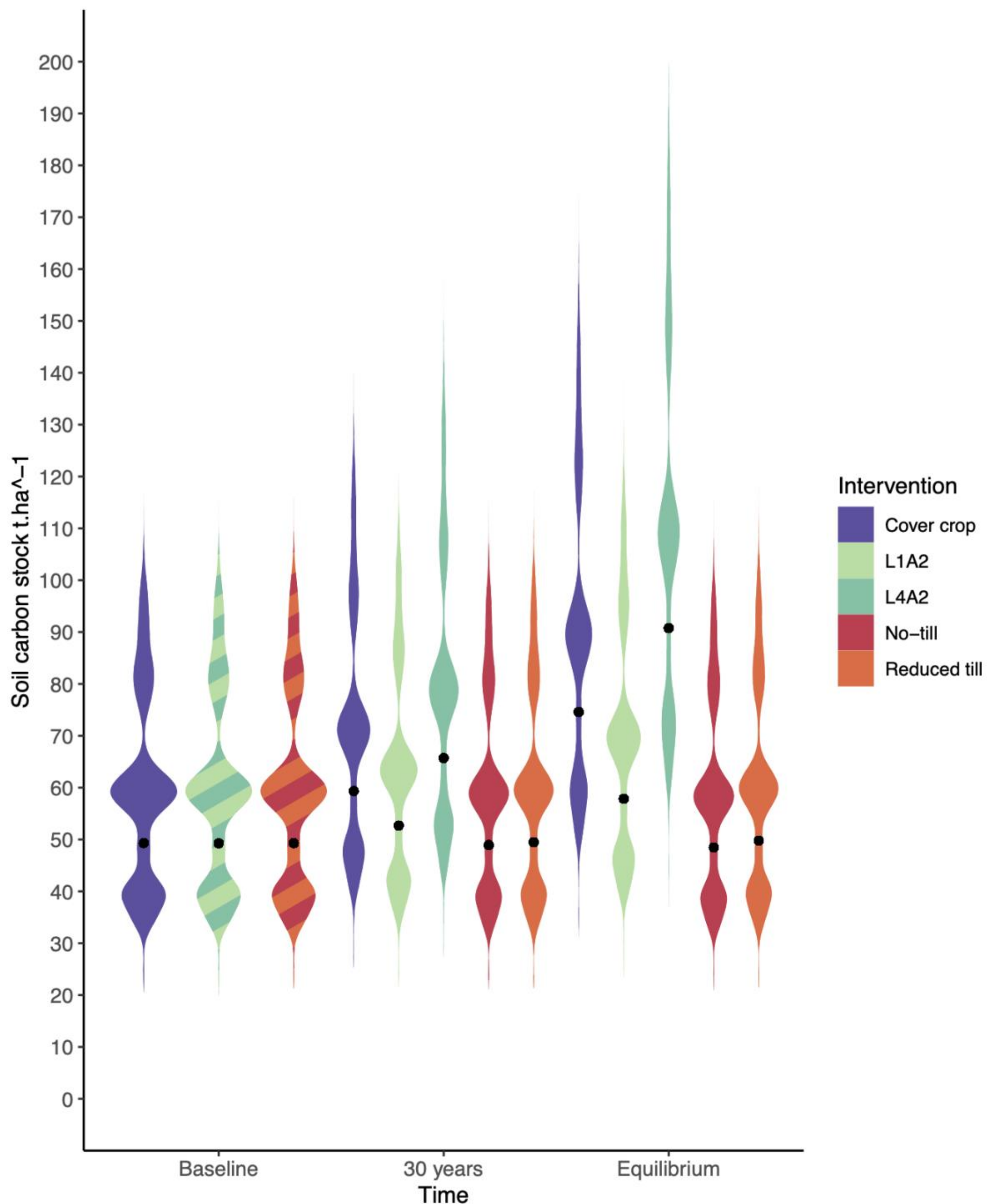


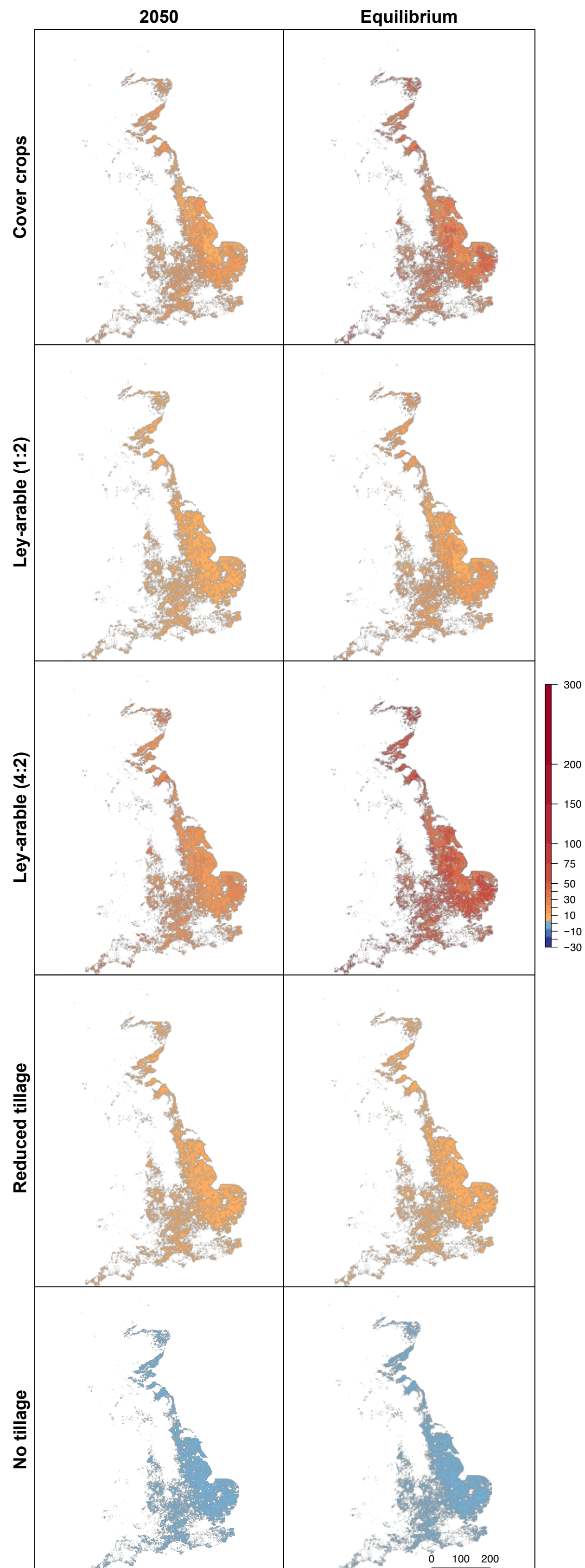
Figure 5.1. Distribution of Great Britain arable soil organic carbon (SOC) stocks (t.ha^{-1}). Baseline (assumed current, using WISE30sec values) (Batjes, 2016) and following implementation of cover crops, ley-arable rotations and reduced tillage intensity after 30 years (i.e. around the year 2050) and once a new equilibrium is reached, to 30 cm depth. Violin plots show distribution of mean values from each 1 km^2 model run for in Great Britain. Two ley-arable systems are modelled: L1A2, one year ley-phase and two years arable cropping, and L4A2, four years ley-phase and two years arable cropping. Simulations for two ley-arable scenarios and two reduced tillage scenarios were run together, respectively, hence shared baselines.

5.5.2. Sources of uncertainty and limitations

Our results are not directly comparable with the findings of similar studies due to differences in i) the area of arable land that management changes are modelled over, ii) assumptions regarding level of adoption of management change (e.g. length of ley phase in ley-arable rotation or proportion of rotation that cover crops are included), and iii) soil and climate inputs in other study countries (Dendoncker et al., 2004, Taghizadeh-Toosi and Olesen, 2016, Smith et al., 2000a, Robertson and Nash, 2013). Furthermore, our estimate of total baseline (i.e. current) SOC stock in GB arable farmland (Table 5.3) does not match other estimates (Bradley et al., 2005, Smith et al., 2000a), in part because, to be conservative, we used survey data of the area of arable crops grown in 2021 to weight our output, rather than total cropable area. However, our baseline per area average of 49.3 t $C.ha^{-1}$ in the 0-30cm horizon is close to the European average of 53 t $C.ha^{-1}$ (Smith et al., 2000b). Further, our estimate of baseline Plant Residue Input (PRI) for GB arable land was 3.30, 95% Credible Intervals [3.295, 3.298], which is acceptably similar to Falloon et al. (2006)'s estimate of 3.67 (Standard Deviation 1.71).

Spatial heterogeneity in the magnitude of SOC stock change across GB (Fig 5.2) is predominantly due to existing variation in GB soil carbon stocks (Fig A3.1). In the cover crop simulation, baseline SOC stock (determined from WISE30sec SOC concentration and bulk density data) alone explains 99.7% of total variation in SOC stocks after 30 years of treatment implementation (Fig A3.2). WISE30sec values are derived from the Harmonised World Soil Database, and therefore the European Soil

Database for GB, using a taxotransfer scheme (Batjes, 2016) and come with standard deviations that capture the uncertainty in these estimates, which we propagated through our modelling framework. However, our large sample size (>61,000 pixels, 100 model iterations per pixel) means the uncertainty around our overall estimates is acceptably small (Table 5.3). Our modelling approach used baseline SOC to calculate initial PRIs, which were then proportionally increased for cover crops and ley-arable scenarios, resulting in variation within the soils input data being amplified in our modelling outputs (Fig 5.2). Although climatology inputs (monthly average temperature, precipitation, and evapotranspiration (Abatzoglou et al., 2018)) explained 7.25% of variation in GB baseline PRI estimates, these parameters explained only 0.1% of variation in SOC stock estimates at 2050 (Fig A3.2). Conversely, in our model calibration stage, climatology inputs explained 38% and 25% of variation in estimates of study baseline and endline PRI, respectively (Fig A3.3). This is likely because studies used for model calibration were from across temperate oceanic regions, which have greater variation in climate than within GB, aligning with previous sensitivity analyses with RothC that have demonstrated a strong influence of climate variables on predicted SOC (Janik et al., 2002). Soil carbon concentration ($g.100g^{-1}$) explained 27% and 35% of variation in baseline and endline PRIs respectively (Fig A3.3).



2050
Equilibrium
Cover crops
Ley-arable (1:2)
Ley-arable (4:2)
Reduced tillage
No tillage
300
200
150
100
75
50
30
10
−10
−30
0
100
200

Figure 5.2. Great Britain arable soil organic carbon (SOC) stocks (t.ha^{-1}) at 1 km^2 resolution. Colour indicates difference from baseline (0-30 cm), following implementation of cover crops, ley-arable rotations and reduced tillage intensity after 30 years and once a new equilibrium is reached. The two scenarios for ley-arable rotations are one year ley-phase and two years arable cropping (L1A2), and four years ley-phase and two years arable cropping (L4A2). 1 km^2 resolution for arable land in Great Britain identified using the CEH land cover map (Rowland et al., 2017).
Scale bar in km.

Using an inverse modelling approach to estimate PRI in RothC assumes that SOC stocks are at equilibrium. If SOC is in fact increasing or decreasing, then the PRI would be underestimated or overestimated respectively (Falloon et al., 2006). We use this inverse modelling step both in our model calibration and spatially explicit simulation. Studies used to calibrate our model framework ranged in duration from 2 to 70 years (mean 15) (Jordon et al., 2022) which is insufficient for SOC to reach a new equilibrium following a change in management (50-150 years for a decrease, 100-750 years for an increase (Falloon et al., 2006)), and therefore the proportional changes in PRI we calculated from studies of cover crops and ley-arable duration are at risk of being underestimated. Further, there is evidence that SOC in much of GB's arable land is still in the process of decline following conversion from grassland in previous decades (Skinner and Todd, 1998), and therefore our estimates of baseline PRI for proportional adjustment are possibly overestimates. Conversely, there are two additional mechanisms by which the baseline PRIs we calculated for GB arable soils could be overestimates. Firstly, use of 1 km^2 resolution soil data means that some squares may in reality contain a combination of mineral and organic soils. RothC is not suited for use on organic and organo-mineral soils because it over-predicts the PRI required to maintain the high SOC concentration in these soils. Although we excluded WISE30sec pixels with a SOC concentration

above 100 g.kg^{-1} from our analysis, pixels with mixed soil types could result in a SOC concentration higher than a typical mineral soil but under our 100 g.kg^{-1} threshold, leading to an overprediction of current PRI for these pixels. This could also potentially explain the clustered rather than Gaussian distribution of baseline SOC stocks (Fig 5.1), although the derivation of WISE30sec soil properties using taxotransfer rules is also likely responsible for this clustered distribution by reflecting underlying discreet soil type categories. Secondly, using the CEH dominant land class product means that each 1 km^2 could contain large areas of other land uses with typically higher SOC, such as permanent pasture or woodland, again inflating the SOC concentration used to infer PRIs on arable land. Because our modelling framework proportionally adjusted baseline PRI to simulate cover cropping or ley-arable adoption, any overestimation of PRI would in turn lead to an overestimate in the SOC stock change possible from adopting these interventions on mineral arable soils alone. Despite this, our estimates of GB baseline SOC stocks and potential changes following adoption of RA practices are consistent with previous studies using other approaches and input datasets, and we are confident in our results as indicative of the trends possible.

Our modelling framework does not identify significant GHG mitigation potential from reducing tillage intensity or no till, in contrast with previous estimates (e.g. Smith 2000, Dendonker 2004). This could be because the tillage rate modifiers (TRM) developed in Jordon and Smith (2022) were calibrated to empirical data which, when recently meta-analysed, show only very small increases in SOC concentration when

reduced or no tillage are adopted in temperate oceanic regions compared to conventional full-inversion tillage (Jordon et al., 2022). Alternatively, although Jordon and Smith (2022) endeavoured to best represent the mechanism of soil carbon increases following a reduction in tillage intensity by developing a TRM rather than adjusting PRI, in reality these two mechanisms are likely to be confounded in some instances. This is because reduced tillage or no till are often implemented as part of a broader conservation agriculture approach where arable stubble is retained instead of removed as straw, thus potentially increasing carbon inputs to the soil alongside decreasing the rate of decomposition. Identifying these two mechanisms *via* an inverse modelling approach would require a dataset with factorial treatments of tillage intensity and straw retention to establish the PRI increase from straw retention, tillage rate modifier from reduced tillage intensity, and any interaction between these. Further, a depth-distributed model would likely better account for SOC dynamics following reduced tillage intensity (Angers and Eriksen-Hamel, 2008), but would similarly require calibration from depth-distributed studies.

We do not include scenarios to account for the impact of near-future climate change on soil carbon stocks and the way this could interact with the efficacy of land management changes to sequester soil carbon. We would expect increases in average temperature and/or precipitation to increase the rate of decomposition of carbon inputs to the soil, resulting in a modest decline in soil carbon for a given PRI (Zhong and Xu, 2014, Sakrabani and Hollis, 2018, Smith, 2012) and any increase in

PRI following adoption of cover crops or ley-arable system to deliver less of an increase in SOC stocks.

5.5.3. Greenhouse gas mitigation potential

We identify GHG mitigation potential for Great Britain (GB) in the next 30 years of 6.48 million tonnes of carbon dioxide equivalent per year ($MtCO_2e.y^{-1}$) if cover crops were grown on arable land (Table 5.3), assuming no prior adoption. A scenario of low ley-arable integration (L1A2) would deliver 2.19 $MtCO_2e.y^{-1}$ over 30 years, or 10.6 $MtCO_2e.y^{-1}$ if higher adoption (L4A2) (Table 5.3). In contrast, our results imply that adopting no till could result in net GHG *emissions* of 0.234 $MtCO_2e.y^{-1}$ due to decreases in SOC stocks, and reduced tillage only limited sequestration of 0.11 $MtCO_2e.y^{-1}$, over 30 years (Table 5.3). Although SOC changes would continue for longer than 30 years for all interventions until a new equilibrium is reached, we focus on a 30-year time horizon to assess the potential climate change mitigation potential of these RA practices due to the significance of the year 2050 for meeting domestic and international net zero GHG emission targets (IPCC, 2018, Climate Change Committee, 2019). Furthermore, because soil carbon dynamics are non-linear and the time to reach a new equilibrium varies between interventions, expressing the final total change in SOC stocks as an annualised rate does not best reflect the timescale of SOC changes.

To contextualise our results, the total GHG emissions of Great Britain were 433.4 $MtCO_2e$ in 2019, of which agriculture comprised ~40 $MtCO_2e$ (United Kingdom

emissions (BEIS, 2021) minus Northern Ireland (Daera, 2019)). Full adoption of cover crops from a baseline of zero adoption could therefore mitigate around 16% of GB agriculture's emissions between now and 2050, and high inclusion of leys in arable rotations could mitigate 27% of current agricultural emissions. This comes with the major caveats that these interventions are in fact already implemented to some extent in GB and assumes an ability to achieve immediate adoption across all remaining arable land, which is unrealistic. Nevertheless, we identify emissions abatement potential from adopting RA practices of a comparable magnitude to previous scenarios of changes in UK land management, which have estimated 10 $MtCO_2e.y^{-1}$ from soil carbon sequestration (Royal Society and Royal Academy of Engineering, 2018) and 10 $MtCO_2e.y^{-1}$ from adoption of low-carbon farming practices (Climate Change Committee, 2020) for the UK. Alternatively, adopting cover crops and a high frequency of ley-phase in arable rotations through our 'land-sharing' approach to carbon sequestration would sequester 9 and 14%, respectively, of the ~74 $Mt.CO_2e.y^{-1}$ abatement theoretically possible under an upper-bound scenario of agricultural yield increases sparing UK land for afforestation with coniferous woodland (Lamb et al., 2016). Furthermore, our findings concur with previous work that have found limited potential for carbon sequestered through changes in farm management to mitigate even agricultural GHG emissions (MacLeod et al., 2010, Franks and Hadingham, 2012), much less provide carbon offsets to other sectors (Schlesinger and Amundson, 2019).

In addition to previously characterised barriers to adoption of RA practices by land managers (Mills et al., 2020), there are key practical limitations to the implementation of practices considered here for climate change mitigation. Establishing cover crops rather than leaving bare arable stubbles or cultivated soil over winter benefits water quality and soil nutrient retention (Abdalla et al., 2019), with this practice already being promoted for these reasons. However, many crops commonly grow in GB arable rotations are established in the autumn (e.g. winter wheat or winter oilseed rape) (Defra, 2019) which are less compatible or incompatible with over-winter cover crops. A shift to spring-sown cultivars would likely incur a yield penalty e.g. (Vijaya Bhaskar et al., 2013, Cormack, 2006), which is a disincentive for farmers and risks displacing cultivation elsewhere. Similarly, ley-arable rotations are already commonplace in organic farming systems due to the fertility-building properties of the ley phase (particularly if containing legumes) benefiting the following arable crop and are increasingly being adopted in conventional systems as a tool to control crop weeds displaying herbicide resistance, such as blackgrass (*Alopecurus myosuroide*). However, each year of ley phase in a rotation has an 'opportunity cost', with possible revenue streams from a ley (e.g. grazing with livestock, harvesting fodder for livestock or as anaerobic digestor feedstock) typically less profitable than producing an arable crop. Furthermore, if demand for arable crops did not decrease in proportion to the increase in ley-phase in arable rotations (e.g. through a restructuring of livestock production away from indoor rearing or finishing on cereal-based rations to grazing or ranging over temporary leys in arable systems (Lee et al., 2021, Karlsson and Röös, 2019), this would result in compensatory cultivation of

pasture in GB or displaced land use change overseas, the emissions from which would likely more than offset any carbon sequestration from ley-arable adoption (Carlton et al., 2011, Ostle et al., 2009). Our modelling approach suggests that reduced tillage intensity does not substantially build soil carbon stocks, if at all, in this temperate region. A further limitation of implementing this practice on soils with compromised structure is the risk of increased soil compaction leading to higher emissions of nitrous oxide (Huang et al., 2018, Powlson et al., 2014). This could potentially result in a net increase in GHG emissions, limiting the role of reduced tillage intensity for climate change mitigation in this context. We do not consider environmental or policy restrictions on the implementation of these practices or features of current GB farm structure which have been shown elsewhere in Europe to further limit GHG mitigation potential of these practices (Dendoncker et al., 2004, Taghizadeh-Toosi and Olesen, 2016). Further work could combine our approach here with data on current farm management and cropping practices, in addition to economic and behavioural models, to estimate the likely capacity for further adoption of these practices in a GB context.

5.6. Conclusions

Adopting the Regenerative Agriculture practices of cover cropping and ley-arable rotations on cropland in Great Britain has potential to substantially increase carbon stocks within 30 years, mitigating up to a quarter of agricultural GHG emissions. Although the modelling uncertainty within our estimates is acceptably small, there are clear practical barriers to achieving complete adoption of these practices across

all GB arable land. While gains in SOC stocks from adopting such practices are worth pursuing where trade-offs with current management systems and rotations can be minimised, our results demonstrate the challenges of relying on boosting soil carbon sequestration to abate ongoing agricultural emissions.

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Chapter 6. Rotational grazing and multispecies herbal leys increase productivity in temperate pastoral systems – a meta-analysis

6.1. Summary

This chapter describes the results of a systematic review with meta-analysis that I undertook to examine the evidence base regarding the impact of RA practices in grazing systems on SOC and productivity. This completes my work towards addressing my first aim. I assembled a dataset of the impact of rotational grazing and herbal leys on pasture dry matter yield, sheep and cattle growth rates, and sheep wool production by extracting data from papers identified in my systematic review. I then used Bayesian meta-analyses to identify the relative effects on pasture productivity and livestock growth on these land management practices. My work demonstrated that rotational grazing increases both pasture productivity and livestock growth in proportion to the period in the rotation which grass was ungrazed (i.e. rested) so allowed to recover. Regarding herbal leys, it became apparent from my work that root depth, proportion of legumes and species diversity positively predict forage production, and leaf nitrogen content positively predicts sheep growth rates. In contrast to productivity metrics, there are insufficient published studies of SOC under these two other management practices (rotational grazing and herbal leys) for quantitative meta-analysis. I therefore discuss the potential mechanisms by which these practices may affect this.

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Rotational grazing and multispecies herbal leys increase productivity in temperate pastoral systems – a meta-analysis

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6.2. Abstract

Reducing greenhouse gas emissions associated with ruminant livestock production is important for climate change mitigation. Regenerative Agriculture (RA) practices are increasingly promoted to improve forage production and livestock performance in temperate livestock systems. These practices include i) rotational grazing (RG) of livestock around multiple subunits of pasture to achieve ungrazed periods of 'rest', and ii) herbal leys (HL), where perennial forbs such as chicory, lucerne and trefoils are included as components in multi-species swards. While there are plausible mechanisms for adoption of these practices to improve agricultural productivity, quantitative syntheses of their impacts are required. Here, we conduct a systematic review and meta-analysis of the effects of RG and HL practices on herbage dry matter (DM) production, animal daily liveweight gain (DLWG), and sheep wool growth in temperate oceanic regions. We use quantitative predictors in our Bayesian hierarchical models to investigate the role of rest period and stocking density in RG systems, and specific plant traits and sward diversity in HL. We found that herbage

DM increased by 0.31 $t.ha^{-1}$ over a growing season as the proportion of rest in an RG grazing system increased from 0 to 1. Stocking density significantly moderated the effect of rest period on sheep and cattle DLWG; at higher stocking densities, longer rest periods were required to maintain livestock growth rates. In HL studies, herbage DM yielded 1.63 $t.ha^{-1}$ more per metre of increased sward root depth and a sward entirely comprised of legumes yielded 2.20 $t.ha^{-1}$ more than when no legumes were present. Sheep DLWG increased by 3.50 $g.day^{-1}$ per unit increase in leaf nitrogen concentration ($mg.g^{-1}$), but we could not determine an effect of leaf condensed tannin content on animal performance. Although there remain differences between the RG and HL study treatments meta-analysed here and RA in practice, our results provide empirical support for some of the mechanisms attributed to increased pasture and livestock productivity following adoption of selected RA grazing practices.

6.3. Introduction

Global food production is responsible for 30% of anthropogenic greenhouse gas emissions, causing climate change (Clark et al., 2020). Ruminant livestock significantly contribute to these emissions, particularly through methane produced via enteric fermentation (Gerber et al., 2013, Godfray et al., 2018, Herrero et al., 2011). The short-lived nature of methane in the atmosphere has led to calls for reduced livestock production in order to deliver rapid emissions reduction as a quick win for climate change mitigation (Smith and Balmford, 2020). Alternatively, or in addition, avenues to reduce emissions associated with ruminant-sourced foods

include: enhancing livestock health and fertility to reduce livestock numbers required for a given level of food produced, using feed additives to inhibit enteric methane production, increasing growth rates to reduce lifetime emissions, and improved feed quality and digestibility which lowers methane production (Herrero et al., 2016, Hristov et al., 2013). These latter two options can be pursued at least in part through adopting management practices which improve productivity in sheep and cattle grazing systems.

Simultaneously, Regenerative Agriculture (RA) practices are rapidly gaining attention as a means to improve pasture and livestock productivity in temperate grazing systems through enhancing soil health and promoting ecosystem functioning. These include rotational grazing (RG), which can be defined as "the movement of livestock between two or more subunits of pasture such that alternating periods of grazing and no grazing (rest) occur within a single growing season" (Briske et al., 2011b) [2]. Further, herbal leys (HL) incorporate perennial forbs and legumes into pasture swards, including chicory (*Cichorium intybus*), birdsfoot trefoils (*Lotus corniculatus* and *L. pedunculatus*), lucerne (*Medicago sativa*), plantain (*Plantago lanceolata*), sainfoin (*Onobrychis viciifolia*), sulla (*Hedysarum coronarium*) and yarrow (*Achillea millefolium*) e.g. (Barry, 1998, Li and Kemp, 2005, Douglas, 1986, John and Lancashire, 1981, Stewart, 1996) with the aim of benefiting from certain properties of

[2] We use 'rotational grazing' throughout as a catch-all term for all grazing systems that fall within this definition, including mob grazing, cell grazing, paddock grazing, controlled grazing, holistic planned grazing, adaptive multi-paddock grazing, strip grazing or precision grazing. We use proportion rest period and stocking density as quantitative predictors in our meta-analysis (see Methods, Section 6.4.2.1), as the simple categories of continuous vs rotational grazing are inadequate to capture the diversity of practices covered by this term.

these species. These practices occur on spectra of grazing management and sward diversity, respectively (Fig 6.1).

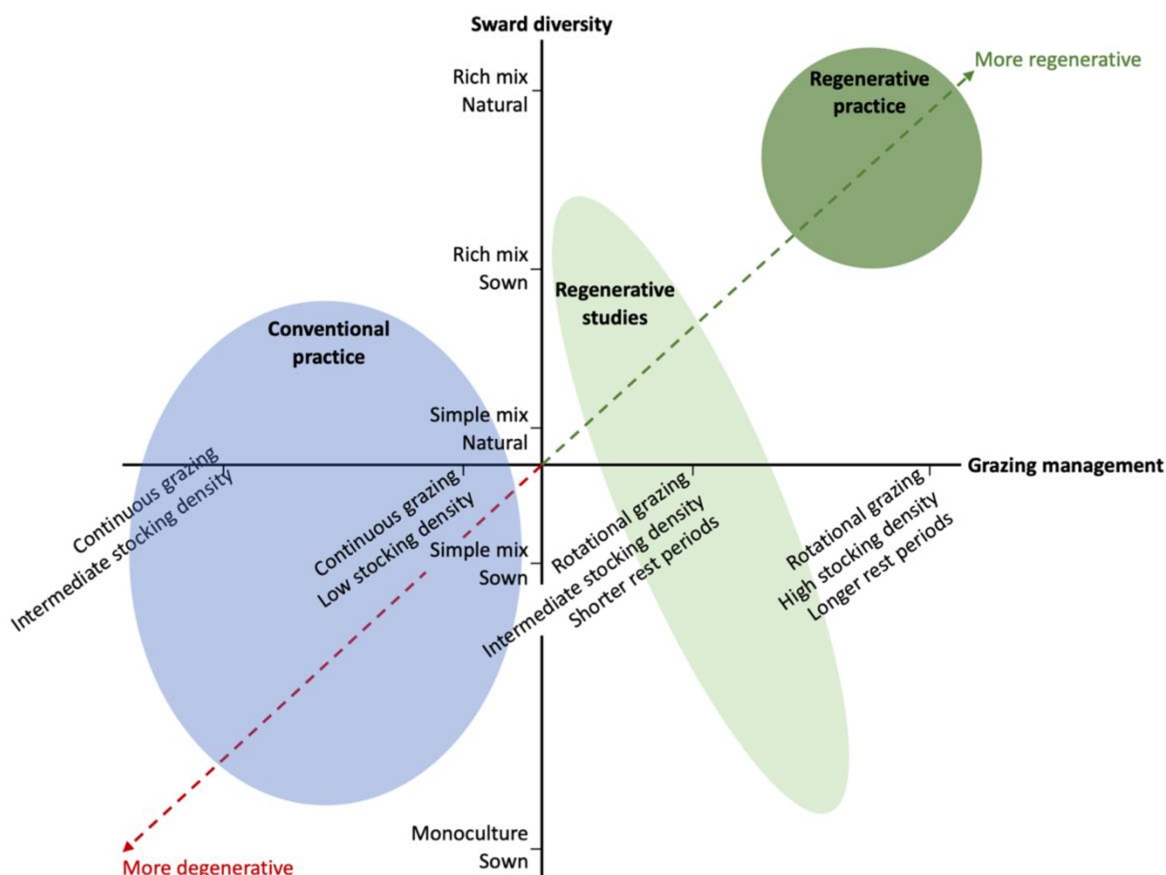

Figure 6.1. Conceptual diagram of spectra of grazing management intensity and pasture sward diversity. Rotational grazing and herbal ley practices fall along the x and y axes, respectively. These interact particularly in the lower left and upper right quartiles, where continuous grazing pressure can reduce sward diversity by removing palatable or sensitive species, and mob grazing can increase the natural sward diversity through unselective grazing and periods of rest, respectively. Note that the management implemented by Regenerative Agriculture practitioners is often of a higher intensity on these axes compared to published studies of rotational grazing and herbal leys analysed here. Although not displayed, the positive or negative effects of these practices are likely to saturate or plateau with time.

Conventional lowland livestock management practices in temperate countries such as the United Kingdom (UK) often comprises continuous grazing or ‘set stocking’ of often low diversity pastures comprising a small number of grass species,

predominantly perennial ryegrass (*Lolium perenne*), timothy (*Phleum pratense*), cocksfoot (*Dactylis glomerata*) and fescues (*Festuca spp*.), in addition to white and red clovers (*Trifolium repens* and *T. pratense*, respectively) (Wilkins and Jones, 2000). More 'regenerative' pasture management increases sward diversity to include a mix of grasses, legumes and forbs (either by sowing these or creating the conditions for them to persist or re-establish naturally) and increases the proportion of the growing season that pastures are rested (usually accompanied by higher stocking density when grazed), i.e. moving further up and to the right, respectively, of the conceptual axes in Fig 6.1.

Interest in RA is relatively recent (Giller et al., 2021), but RG and incorporation of forbs into pastures (HL) have been promoted for over a century in temperate regions, for example to restore degraded rangeland in North America and as part of ley farming systems in Western Europe, respectively (Voisin, 1959, Briske et al., 2011b, Elliot, 1908, Turner, 1951).

RG is purported to increase livestock productivity (e.g. animal liveweight gain, milk production, or wool growth) and pasture carrying capacity via enhancing forage productivity. Periods of rest following removal of livestock grazing pressure are thought to allow enhanced root development which enables rapid regrowth of herbage following infrequent defoliations, compared to smaller root systems and permanently low leaf photosynthetic area under continuous grazing pressure (Sanderman et al., 2015, Hacker, 1993, Voisin, 1959, Savory and Butterfield, 2016).

Further, decreasing the area available to livestock at any one time through subdivision of pasture into paddocks may reduce selectivity of animal grazing, preventing less palatable species from dominating the sward and deteriorating forage quality, plus achieving more uniform distribution of livestock manure and urine across the pasture (Briske et al., 2008, Norton, 1998). These effects are believed to be accentuated under longer rest periods, typically corresponding with shorter grazing periods and higher stocking densities to match forage availability with livestock requirements. However, although these mechanisms are plausible and convincing to many land managers, they are predominantly based on scientific theory, and the currently available scientific evidence has been found to be inconclusive for USA rangelands (Briske et al., 2008, Briske et al., 2011a, Briske et al., 2011b).

HL (and greater sward diversity more broadly) may enhance livestock productivity both 'indirectly' via improved pasture productivity but also directly via specific properties of the herbage of individual species, compared to grass-only swards. Pasture productivity is increased predominantly through enhanced niche complementarity due to greater species diversity, with mechanisms including i) greater variation and depth in rooting structures both conferring drought tolerance, thus stabilising forage quality and supply throughout the grazing season (Cranston et al., 2015), and improving nutrient uptake through accessing different soil profiles (Li and Kemp, 2005, Stewart, 1996), ii) legumes fixing atmospheric nitrogen (Luscher et al., 2014) and in turn increasing N availability to other sward components (Suter et

al., 2015), iii) increased resilience of production across varying growing conditions (Skinner and Dell, 2016, Sanderson et al., 2005), and iv) functional redundancy (Weisser et al., 2017). Herbage from these swards can also have a higher nutritive value, including increased crude protein content (Cranston et al., 2015, Luscher et al., 2014), improved palatability leading to higher uptake (Wilkins and Jones, 2000, Burke et al., 2002), and enhanced mineral content (Barry, 1998), which may contribute to increased livestock productivity.

Some herb species also contain secondary metabolites such as condensed tannins (CT) which can protect protein from degradation in the rumen, thus potentially increasing uptake in the animals' intestines. Although plausible, this mechanism may be limited in practice because i) CTs vary in their bioactivity and impact on forage palatability and digestibility, mediated by their concentration, molecular structure and the wider dietary composition, ii) recent studies indicate CTs may simply shift excretion of dietary nitrogen excretion from urine to faeces rather than increase net N uptake, iii) CTs may only confer a nutritional benefit when dietary protein exceeds animal requirements in which case other nutrient deficits may limit performance, and iv) CT-rich species tend to compete poorly in swards resulting in limited inclusion in the diet (Grosse Brinkhaus et al., 2016, Mueller-Harvey et al., 2019, Loza et al., 2021). Nevertheless, CTs can reduce intestinal parasitic worm burdens, and methane and nitrous oxide emissions associated with livestock production (Fox et al., 2018, Luscher et al., 2014, Mueller-Harvey et al., 2019).

Despite compelling and plausible mechanisms for these regenerative grazing practices to increase productivity, there is currently a paucity of quantitative syntheses that test these relationships (Briske et al., 2011b, Conant et al., 2017). Here, we provide a meta-analysis of data presented in previously published studies to examine the impacts of RG and HL on pasture and livestock productivity in temperate oceanic regions (Köppen-Geiger Cfb), conducting a systematic review to assemble a database of relevant studies. We test the hypothesis that these regenerative practices increase plant and animal productivity, using quantitative predictors in our Bayesian hierarchical analyses to evaluate possible mechanisms for this. We aim to establish whether sufficient evidence exists to promote adoption of selected regenerative grazing practices in temperate regions to deliver the benefits currently attributed to these.

6.4. Methods

6.4.1. Systematic review

We followed the Collaboration for Environmental Evidence guidelines (CEE, 2018) to address the systematic review question “What are the impacts on soil carbon and farm productivity from adopting rotational grazing practices and incorporating perennial forbs into pastures (herbal leys) in temperate oceanic sheep and cattle farming systems?”, using the Population, Intervention, Comparator, Outcome and Location (PICOL) framework (Table A4.1). Full details of our systematic review following the Reporting standards for Systematic Evidence Syntheses (ROSES) framework (Haddaway et al., 2017b) are given in Appendix 4.1. All data extracted

from relevant studies of RG and HL, further supplementary files and R code are available online in the Zenodo repository (Jordon, 2022).

We conducted searches in Web of Science, CAB Abstracts and Scopus (details in Table A4.2, Appendix 4.1.1) and undertook ‘reverse snowballing’ of citations from reference lists of included articles until no additional relevant records were returned (Table A4.3, Appendix 4.1.1.1). We screened records at title, abstract and full text levels using pre-determined inclusion and exclusion criteria (Table A4.4, Appendix 4.1.2). Data from relevant studies were extracted to a spreadsheet (Appendix 4.1.3), with any extra calculations to convert data to the required format documented in this datasheet and conducted in individual Excel files for each article, available online (Jordon, 2022). Each study was assigned a critical appraisal score reflecting the quality of experimental design (Table A4.5). As it is well-established in systematic reviewing that not all evidence is of equal quality and therefore validity (CEE, 2018), we adapted a critical appraisal scoring approach from Haddaway et al. (2017a) as a means of testing the sensitivity of our meta-analysis results to studies with the highest risk of bias (low or unclear validity, Appendices 4.1.3 & 4.2.2). This is not an assertion that results from such studies are invalid, but rather to ascertain the strength of conclusions from our analysis. Where desired data was missing from articles (Tables A4.6-7), we attempted to contact the corresponding author with a request for data (Appendix 4.1.4). We received responses from authors of five articles, of which three were able to provide additional information and are thanked in the Acknowledgments.

Table 6.1. Number of studies that measured each outcome for rotational grazing and herbal leys identified by systematic review. Values in brackets are number of studies where standard errors are presented for estimates. The sum of outcomes listed here is greater than the number of studies identified by the systematic review because some studies present multiple outcomes.

	Outcome	**Livestock type**	**Unit**	**Intervention** **Rotational grazing**	 **Herbal leys**
	Soil organic carbon	n/a	$g.100g^{-1}$	-	1 (1)
			$t.ha^{-1}$	2 (2)	1 (1)
Productivity measure	Herbage dry matter	n/a	$t.ha^{-1}$	13 (3)*	42 (14)*
	Daily liveweight gain	Sheep	$g.day^{-1}$	5 (2)*†	50 (28)*
		Cattle		3 (3)*†	1 (1)
	Milk yield	Sheep	$kg.day^{-1}$	-	1 (1)
		Cattle		4 (0)	5 (1)
	Wool growth	Sheep	$mg.cm^{-2}.day^{-1}$	-	7 (5) *
			$g.day^{-1}$	3 (0)	7 (6) *

- No studies report this intervention-outcome combination.
* Intervention-outcome combinations where sufficient data to conduct quantitative meta-analyses.
† Daily liveweight gain for cattle and sheep under rotational grazing vs set stocking was analysed together, with livestock type as a fixed effect in the analysis.

Our systematic review resulted in a database of 84 articles containing 115 studies across 9 countries with temperate oceanic regions (Figs 6.2 & A4.1). From this, we extracted 101 observations from studies of rotational grazing vs set stocking, and 485 observations from studies of herbal vs conventional leys (Jordon, 2022) for quantitative meta-analysis or narrative synthesis (Table 6.1). Where values for required predictor variables were not provided in articles and could not be retrieved from study authors, these observations were excluded from meta-analyses, resulting in fewer observations analysed than present in the dataset (number of observations specified in results table for each analysis).

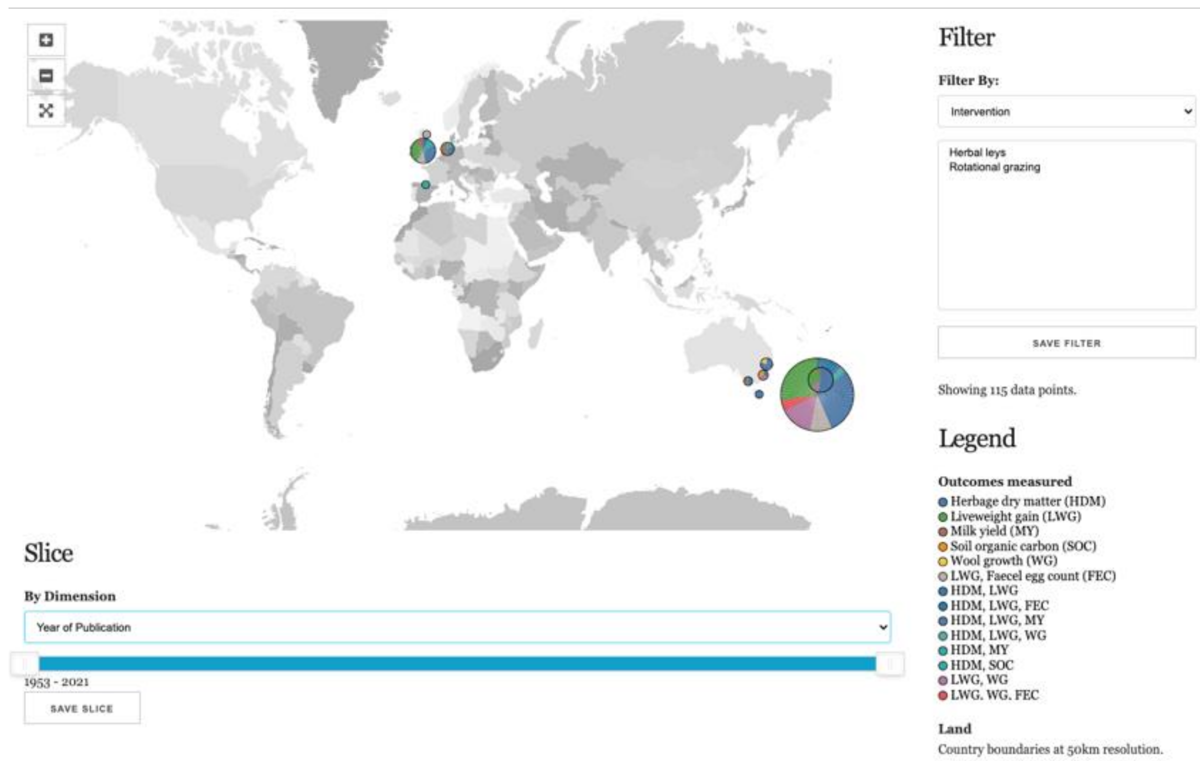

Figure 6.2. Evidence map. 115 relevant studies identified by systematic review process for inclusion in meta-analysis, created using the Thalloo framework (Martin, 2018). Position of pie charts reflects study locations (degrees decimal coordinates), size of pie charts is proportional to the number of 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/agricultural_productivity/

6.4.2. Meta-analysis

We fitted Bayesian hierarchical (i.e. random effects) models using the *brms* package in R version 4.0.3 (Bürkner, 2017, Bürkner, 2018, Stan Development Team, 2019, R Core Team, 2020). We analysed herbage dry matter (t.ha^{-1}), livestock daily liveweight gain (g.day^{-1}) and wool growth (mg.cm^{-2}.day^{-1} and g.day^{-1}) data extracted from studies, as these were the systematic review outcomes (Table A4.1) with sufficient data available for meta-analysis (Table 6.1). The data points we analysed (rows in our dataset) were outcome means per treatment per study in our systematic

review. We did not compute comparative effect size metrics (i.e. between treatments, or between control and treatment), because there are substantial differences in treatment interventions both within and between studies. Instead, the comparison was directly encoded via the hierarchical structure of our Bayesian models. Further, the interventions analysed here are best expressed using continuous rather than categorical predictors (see Sections 6.4.2.1-3), enabling a more informative analysis. Within each response variable, data across all treatments and studies are directly comparable on the same scale and our approach has the advantage that outputs from the model are readily understood. In addition, we centred all continuous predictors around their respective means so that the model output intercept was biologically meaningful, rather than corresponding to predictor values of zero which are often not possible.

Our R code is available online (Jordon, 2022). Details on model sampling are given in Table A4.8 and model summary outputs are given in Appendix 4.2.3. We used default priors of *brms*, provided online (Jordon, 2022), which are either weakly informative or uninformative to reduce the risk of incorrectly specified priors biasing model outputs. We checked model convergence using the Rhat diagnostic and ensured effective sample size measures were sufficiently large (Vehtari et al., 2020). Model non-convergence was remedied by increasing the number of iterations for sampling and divergent transitions were addressed by decreasing the sampler step size (Stan Development Team, 2020). We assessed the statistical significance of fixed effect model predictors 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 (Gelman et al., 2019). Both between- and within-study heterogeneity was modelled in the form of corresponding standard deviation parameters (across studies, and across effect sizes within studies, respectively). We imputed standard errors of study effect sizes where these were missing and conducted sensitivity analyses to test the robustness of our methodology (Appendix 4.2.2.)

We plotted the conditional effects of model predictors on productivity outcomes, showing regression lines for individual predictors and interaction terms where all other model predictors are at the reference category, with 95% Credible Intervals. We also displayed the raw productivity data from the underlying studies for each intervention using the *forestplot* package (Gordon and Lumley, 2020) (Appendix 4.2.4). To test for possible publication bias, we conducted Egger's regression test for funnel plot asymmetry using the *regtest* function in *metafor* (Viechtbauer, 2010) for productivity data with errors present (EP) and present the results from this along with funnel plots of herbage dry matter and DLWG effect sizes against their standard errors (Appendix 4.2.7). However, we did not interpret the results from these further, as there are multiple potential sources of funnel plot asymmetry in our data (most notably, substantial heterogeneity between studies and treatments), of which publication bias is only one possible explanation, making this test potentially misleading in either direction.

6.4.2.1 Rotational grazing

The key aspects of grazing systems that are likely to affect pasture productivity and livestock performance are the duration of grazing and recovery periods, and the stocking density during the grazing period (Voisin, 1959, Briske et al., 2008, Briske et al., 2011a, Techio Pereira et al., 2018). Simply analysing grazing practice as a predictor with two levels (rotational vs continuous grazing) is inappropriate for the diversity of management practices included within RG (Sanderman et al., 2015). Therefore, we extracted quantitative parameters of treatments from each study to include in our analyses. Where studies provided a range of values for grazing and rest periods in RG treatments due to management flexibility to match grass growth, we used the median value of this range in analysis. Continuous grazing treatments have no rest period, informatively captured in the analysis as zero, but it is difficult to meaningfully represent their grazing period due to i) differences in grazing season length between studies, and ii) grazing and rest periods in RG treatments typically sum to a total rotation length shorter than the grazing season such that there are multiple rotations per season, making comparison of grazing periods with continuous treatments difficult. Further, grazing and rest periods in our dataset are negatively correlated for RG treatments, making it challenging for our meta-analysis model to identify both predictors. Therefore, we instead expressed grazing practices as the proportion of rest period in the system. This captures information about both the grazing and rest periods, although reduces this to a relative relationship thus sacrificing some information about the absolute magnitude of rest periods.

We fitted the following models as specified in R formula syntax:

$$Herbage\ DM \sim Rest\ period + Latitude + (1|Unique\ study\ ID)$$

$$Liveweight\ gain \sim Rest\ period * Stocking\ density + Livestock\ type + (1|Unique\ study\ ID)$$

where

- *Herbage DM*, study treatment measurement of herbage dry matter ($t.ha^{-1}$) accounting for its sample size (see Appendix 4.2.2),
- *Liveweight gain,* study treatment measurement of daily liveweight gain ($g.day^{-1}$), accounting for its standard error,
- *Rest period*, proportion of time within rotation that paddock rested between grazing in rotational system, automatically zero for set stocking or continuous grazing treatments,
- *Stocking density*, Livestock Units per ha, harmonised using coefficients based on animal feed requirements (Defra, 2010, SAC Consulting, 2020), for the area being grazed at any one time (i.e. individual paddock for RG vs whole field for set stocking),
- *Livestock type*, two-level factor (sheep or cattle),
- *Latitude*, absolute Latitude of the study site (decimal degrees),
- *Unique study ID*, included as a random intercept to account for the hierarchical structure of the data

6.4.2.2. Herbal leys

The purported productivity benefits of including perennial herbs in pasture swards in addition to grasses and clovers are attributed to specific properties of these species, including root depth, nitrogen fixation and leaf crude protein and CT contents (see Introduction). Different herbs commonly included in HL differ in these properties, and studies differ in the herb composition and seed mixes included in their experimental treatments. Because analysing productivity outcomes using herb presence/absence as a categorical predictor would not indicate which features of herbs, if any, influenced productivity, we extracted traits values for root depth, plant nitrogen fixation and leaf nitrogen content from the TRY database (Kattge et al., 2020), and calculated aggregated trait values in addition to species richness and evenness (inverse Simpson's diversity index) for multi-species swards (Appendix 4.2.1). Leaf CT content was not available from TRY for any forage plant species in our dataset so we analysed this separately (Section 6.4.2.3).

We fitted the following models:

$$Herbage\ DM \sim Root\ depth * Legume + Species\ richness +$$
$$Species\ evenness + Latitude + (1|Unique\ study\ ID)$$

$$Liveweight\ gain \sim Root\ depth + Leaf\ N + \ Species\ richness +$$
$$Species\ evenness + Latitude + (1|Unique\ study\ ID)$$

$$Wool\ growth \sim Leaf\ N + (1|Unique\ study\ ID)$$

where

- *Herbage DM*, study treatment measurement of herbage dry matter ($t.ha^{-1}$) accounting for its standard error,
- *Liveweight gain,* study treatment measurement of sheep daily liveweight gain ($g.day^{-1}$), accounting for its standard error,
- *Wool growth,* study treatment measurement of wool growth ($mg.cm^{-2}.day^{-1}$ or $g.day^{-1}$), accounting for its standard error,
- *Root depth*, aggregate root depth for sward (m), weighted average by relative abundance of species present,
- *Leaf N*, aggregate leaf nitrogen content per leaf dry mass ($mg.g^{-1}$) of sward, weighted average by relative abundance of species present,
- *Legume,* aggregate score for nitrogen fixation capacity, corresponding to abundance-adjusted proportion of sward that is leguminous (values 0 to 1),
- *Species richness*, number of species present in sward or seed mix,
- *Species evenness*, inverse Simpson's diversity index for sward or seed mix,
- *Latitude*, absolute Latitude of the study site (decimal degrees),
- *Unique study ID*, included as a random intercept to account for the hierarchical structure of the data

We included fewer predictors in the meta-analysis of wool growth data due to less observations of this productivity outcome (Table 6.1). We only analysed liveweight

gain measured for sheep, because the eight cattle observations would be insufficient to identify a *Livestock type* predictor, as in the RG analysis.

To test whether livestock productivity was being influenced by forage availability or other features of the sward, we fitted an additional model for studies that measured both herbage dry matter and livestock daily liveweight gain:

$$Liveweight\ gain \sim Herbage\ DM + Leaf\ N + (1|Unique\ study\ ID)$$

where the variables are the same as above, apart from *Herbage DM* which does not account for measurement standard error due to the difficulty of representing this within a predictor and *Liveweight gain* is weighted by sample size (n) rather than standard errors (Appendix 4.2.2).

6.4.2.3. Condensed tannins

Although leaf CT content per leaf dry mass ($mg.g^{-1}$) trait data was not available from the TRY database, 15 studies in our dataset measured the tannin content of forage available in their treatments (i.e. whole-forage analysis rather than only CT-rich components of sward). We used these data firstly to investigate the effect of CTs on sheep liveweight gain by fitting the following models:

$$Liveweight\ gain \sim Leaf\ CT * PEG + Latitude + (1|Unique\ study\ ID)$$

$$Liveweight\ gain \sim Leaf\ CT * Leaf\ N + Latitude + (1|Unique\ study\ ID)$$

where

- *Liveweight gain,* study treatment measurement of sheep daily liveweight gain (g.day^{-1}), accounting for its standard error,
- *Leaf CT*, measured leaf condensed tannin content per leaf dry mass (mg.g^{-1}) of sward,
- *Leaf N*, aggregate leaf nitrogen content per leaf dry mass (mg.g^{-1}) of sward, weighted average by relative abundance of species present,
- *PEG*, polyethylene glycol (binds and inhibits CTs), administered to animals (yes/no),
- *Latitude*, absolute Latitude of the study site (decimal degrees),
- *Unique study ID*, included as a random intercept to account for the hierarchical structure of the data

Studies that measured herbage CT content but did not contain PEG treatments were coded as "no" for the *PEG* predictor. We fit these models separately to test different hypotheses, i.e. i) does CT inhibition moderate the effect of high-tannin forages on DLWG, and ii) does leaf CT concentration moderate the effect of leaf protein content on DLWG.

Table 6.2. Estimates of total tannin content (not extractable, protein-bound or fibre-bound), offered to livestock (not selected). For tannin measurements with standard errors, we fitted an intercept-only model in *brms* that generated 'meta-estimates' of tannin content accounting for these standard errors. However, because not all studies presented error terms for tannin measurements, and we anticipate the disadvantage of a smaller sample size outweighs the benefit of accounting for standard error in the average score, we also calculated the arithmetic mean and used this in our analysis model. We present estimates from both approaches for comparison, with 95% Credible Intervals provided for meta-estimates.

Species	Model	Tannin estimate ($g.kg^{-1}$ DM)	Obs	n Studies
Birdsfoot trefoil (*Lotus corniculatus*)	Meta-estimate	25.52 [25.05, 25.96]	13	5
	Mean	26.35	13	5
Greater birdsfoot trefoil (*Lotus pedunculatus*)	Meta-estimate	-	0	0
	Mean	34.44	8	6
Lucerne (*Medicago sativa*)	Meta-estimate	0.30 [0.27, 0.34]	8	3
	Mean	0.50	13	5
Sulla (*Hedysarum coronarium*)	Meta-estimate	45.10 [44.61, 45.61]	5	2
	Mean	28.53	10	4
Perennial ryegrass, white clover (*Lolium perenne, Trifolium repens*)	Meta-estimate	1.25 [0.61, 1.87]	4	2
	Mean	1.38	4	2

Secondly, we used these data to calculate average CT contents for the species or mixes available (Table 6.2). To further understand the implications of plant CT content on animal performance, we investigated their influence on internal parasite burden. Sixteen studies of daily liveweight gain in sheep on HL in our dataset included faecal egg counts (FEC, $eggs.g^{-1}$), a measure of internal parasitic worm burden such as *Nematodirus* and *Trichostrongylus*. We extracted 73 FEC observations from these studies and fitted the following model with FEC as a predictor to verify the effect of worm burden on sheep growth rates:

$$Liveweight\ gain \sim FEC + Latitude + (1|Unique\ study\ ID)$$

where

- *Liveweight gain,* study treatment measurement of sheep daily liveweight gain ($g.day^{-1}$), accounting for its standard error,
- *FEC*, sheep faecal egg count ($eggs.g^{-1}$),
- *Latitude*, absolute Latitude of the study site (decimal degrees),
- *Unique study ID*, included as a random intercept to account for the hierarchical structure of the data

We then investigated whether leaf CT content reduced the worm burden of sheep grazing that herbage, for treatments with sward species compositions present in Table 6.2:

$$FEC \sim Leaf\ CT * Wormer + Latitude + (1|Unique\ study\ ID)$$

where

- *FEC,* study treatment measurement of faecal egg count ($eggs.g^{-1}$), accounting for its sample size (n),
- *Leaf CT*, average leaf condensed tannin content per leaf dry mass ($mg.g^{-1}$) of sward, using values from Table 6.2,
- *Wormer*, anthelmintic treatment administered to animals (yes/no),
- *Latitude*, absolute Latitude of the study site (decimal degrees),
- *Unique study ID*, included as a random intercept to account for the hierarchical structure of the data

We included an interaction term because if leaf CT content did effect FEC, we would expect this impact to be overridden by anthelmintic treatment. Studies that measured FEC and for which leaf CT were available but did not contain information on sheep anthelmintic treatment were coded as level “no” in the *Wormer* predictor.

6.5. Results and Discussion

6.5.1. Rotational grazing

We found that increasing the proportion of the grazing season that pasture is rested as a result of RG improves herbage dry matter (DM) production, with an increase of 0.31 $t.ha^{-1}$ (95% Credible Intervals [0.28, 0.33], Table 6.3, Fig 6.3a) in DM between rest proportions of 0 and 1, corresponding to continuous grazing and continuous rest, respectively. This effect was robust to removal of studies with low or unclear validity (Table A4.9), and accords with results from previous meta-analyses (Badgery and Michalk, 2017, McDonald et al., 2019). However, our result should be treated with caution as too few studies presented measurement standard errors to account for these in the analysis (Appendix 4.2.2) and the fixed effects accounted for very little variation in the data (R^2 0.0751, Table 6.3) with most heterogeneity explained by between-study variation. The effect of rest period on livestock daily liveweight gain (DLWG) changes with stocking density; at low stocking densities the proportion of rest period has little influence on DLWG, but at higher stocking densities rest period positively predicts DLWG (Fig 6.3b). This interaction is significant at the level of 95% Credible Intervals, [0.78, 41.6] (Table 6.3), but should also be treated with caution as most studies analysed were of low or unclear validity (too few studies of

high validity to conduct a sensitivity analysis) and the beneficial effect of rest was not preserved in the sensitivity analysis of studies that presented standard errors (Table A4.9).

Table 6.3. Model estimates of herbage dry matter (DM, t.ha^{-1}) and sheep and cattle daily liveweight gain (DLWG, g.day^{-1}) for studies of rotational grazing. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis. Full model summary outputs presented in Appendix 4.2.3.1.

Outcome	Model†	Intercept	Proportion rest period	Stocking density	Rest period*stocking density	Cattle	Latitude	Standard deviation parameters		R^2		Number of	
								Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
Herbage DM (t.ha^{-1})	WN	3.99 [1.89, 6.21]	0.31 [0.28, 0.33]*	-	-	-	-0.07 [-0.40, 0.31]	0.33 [0.33, 0.34]	3.59 [2.28, 5.82]	0.882	0.0751	19	9
DLWG (g.day^{-1})	EI	-39.4 [-179, 80.1]	221 [2.18, 448] *	-11.1 [-22.4 ,-0.40] *	20.8 [0.78, 41.6] *	787 [596, 978] *	-	14.1 [5.40, 25.4]	108 [61.9, 197]	0.985	0.911	35	8

† WN: meta-analysis weighted by estimate sample size because too few standard errors available, EI: standard errors imputed where missing, see Appendix 4.2.2 for details.

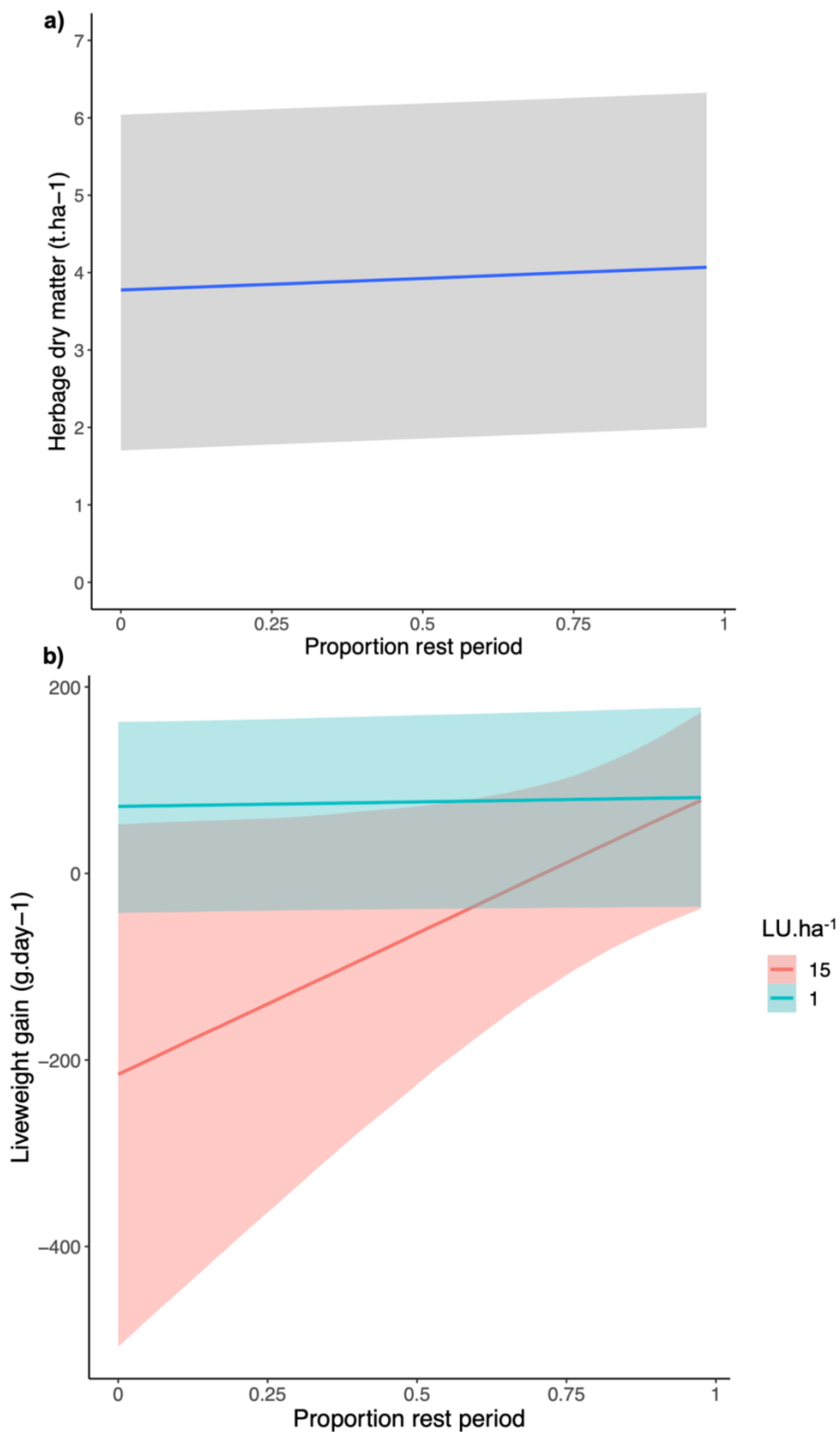

Figure 6.3. Productivity effects of rotational grazing. Conditional effects of **a**) rest period (proportion of grazing season) on herbage dry matter production (DM, t.ha^{-1}), and **b**) rest period (proportion of grazing season) and stocking density (LU.ha^{-1}) on sheep and cattle daily liveweight gain (g.day^{-1}). Error bars show 95% Credible Intervals.

Nevertheless, our DLWG findings accord with expectations from theoretical mechanisms of pasture productivity under RG and our results from the herbage dry matter analysis. At low stocking densities, a period of rest is expected to have little influence on DLWG due to a sufficient forage availability not limiting animal growth, whereas at higher stocking rates longer rest periods are required to allow herbage recovery to meet livestock requirements in the next grazing period. Although not tested here, it is also possible that livestock performance could begin to reduce in systems with the longest rest periods due to declining forage quality with age, mediated by a less favourable ratio of soluble to structural cell components in older tissues (Briske et al., 2008). A previous synthesis from New Zealand identified a disjoint between improved pasture performance not being reflected in improved animal growth (Brougham, 1971), which our results suggest can potentially be explained by the stocking density under consideration. Our findings contrast with results from a recent global meta-analysis and rangeland research trials which typically find that herbage production and animal performance under RG is worse or no better than continuous grazing (Hacker, 1993, Norton, 1998, Briske et al., 2008, McDonald et al., 2019). This may be explained by differences in forage type and climate changing the influence of rest on forage and livestock productivity (Briske et al., 2011a). For example, temperate oceanic regions in our systematic review typically have relatively consistent precipitation throughout the grazing season, allowing forage to utilise periods of rest to recover, compared to more arid rangeland environments where rest periods can achieve only limited forage recovery at low rainfall times of year (Briske et al., 2008). It has also been advocated that to obtain

the greatest productivity benefit from RG, paddock rest periods need to be varied according to the season to account for changes in forage growth rate (Voisin, 1959), although many studies in our dataset applied the same grazing and rest periods across the whole grazing season.

The increase in DM production with lengthened rest period, and the implication from Fig 6.3 that livestock growth rates can be maintained as stocking density increases if rest periods are sufficiently long, appears to suggest that RG can support higher stocking rates than continuous grazing, as has been found in Australia (Badgery and Michalk, 2017) although disputed in a rangeland context (Hacker, 1993, Briske et al., 2008, Hawkins, 2017). In our analysis, however, rest period and stocking density are non-independent within studies. Experimental studies in our dataset often allocated equal total pasture area and animal numbers to RG and continuous grazing (CG) treatments. The RG treatment pasture area is then sub-divided into paddocks with the livestock confined to one of these at a time on rotation, compared to having access to the whole CG pasture area. Rest period is therefore positively correlated to stocking density across RG treatments in our database, as all else being equal increasing rest period requires creating more paddocks by reducing individual paddock size, thus increasing stocking density for a given paddock (Voisin, 1959), rather than overall increasing the livestock carrying capacity of the whole grazing platform. It is therefore difficult to conclude whether high stocking densities on small paddocks and frequent moves confer any actual increase in livestock carrying

capacity over lower stocking densities on larger paddocks with less frequent moves, from the analysis conducted here.

We were unable to fully explore suggested mechanisms for RG practices to increase productivity with our dataset. Although it was necessary to use a proportion to capture grazing and rest period information in our analysis, this prevented us from testing the effect of specific grazing duration on forage and livestock productivity. RA practitioners frequently highlight the importance of frequent moves (<1 to 3 days) to prevent forage regrowth being cropped in the same grazing period, which is believed to negatively impact plant recovery (Voisin, 1959, Savory and Butterfield, 2016) although there are suggestions that the importance of this has been overstated (Hacker, 1993). In addition, RA practitioners often apply a heuristic principle that retaining at least 50% of herbage prevents root death as a plant stress response following grazing, thus enabling more rapid herbage recovery from this maintained root and leaf architecture (Savory and Butterfield, 2016, Brown, 2018). However, we were not able to extract information on the herbage and root biomass before and after each grazing period in rotational systems to determine the influence of the proportion of biomass left as residual on herbage recovery.

6.5.2. Herbal leys

We found herbage dry matter increased by 1.63 $t.ha^{-1}$, 95% CI [0.36, 2.89], per metre increase in sward average rooting depth. There was also an increase of 2.20 $t.ha^{-1}$, 95% CI [1.26, 3.14], when the sward was entirely comprised of legumes

compared to legumes not present (Table 6.4), although note this is purely in terms of interpreting the model result. In practice, there are agronomic limitations to swards entirely comprised of legumes and diversity also positively predicted production (next paragraph). These findings confirm expectations from previous reviews (Cranston et al., 2015, Luscher et al., 2014, Li and Kemp, 2005, Stewart, 1996). Further, the rate of yield increase with greater rooting depth appears to be enhanced when legumes are present (Fig 6.4a), which would be expected from the simultaneous removal of two key limiting factors on plant growth (water and nitrogen). However, we were not able to confirm this positive interaction in our analysis, 95% CI [-0.61, 5.27] (Table 6.4), and the positive impact of root depth was not preserved in sensitivity analyses (Table A4.10). Although HL are purported to stabilise forage production throughout the grazing season by providing better growth in dry conditions (Cranston et al., 2015), we were unable to consider any differences in timing of growth between study treatments in our analyses due to few studies providing sufficient temporal resolution of herbage dry matter measurements.

Table 6.4. Model estimates of herbage dry matter (DM, t.ha^{-1}), sheep daily liveweight gain (DLWG, g.day^{-1}) and sheep wool growth (mg.cm^{-2}.day^{-1} and g.day^{-1}) for studies of herbal leys. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis. Full model summary outputs for herbage DM and DLWG presented in Appendix 4.2.3.1.

Outcome	Model†	Intercept	Root depth	Legume	Root*legume	Leaf N	Herbage DM	Species richness	Species evenness	Latitude	Standard deviation parameters		R^2		Number of	
											Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
Herbage DM (t.ha^{-1})	EI	7.97 [6.05, 9.86]	1.63 [0.36, 2.89] *	2.20 [1.26, 3.14]*	2.33 [-0.61, 5.27]	-	-	0.13 [-0.04, 0.29]	2.76 [0.95, 4.56] *	-0.55 [-0.90, -0.20] *	1.44 [1.21, 1.69]	5.77 [4.59, 7.30]	0.931	0.232	174	41
DLWG (g.day^{-1})	EI	188 [166, 210]	-36.3 [-64.4, -7.28] *	-	-	3.50 [2.17, 4.82] *	-	4.72 [-12.5, 22.2]	-12.48 [-91.54, 64.9]	5.43 [0.74, 10.17] *	46.0 [40.3, 52.5]	70.8 [54.5, 91.0]	0.640	0.199	184	46
	WN	260 [211, 306]	-	-	-	2.80 [2.21, 3.39] *	-4.62 [-5.89, -3.35] *	-	-	-	38.2 [36.8, 39.7]	74.4 [45.4, 122]	0.697	0.0958	34	9
Wool growth	EP (mg.cm^{-2}.day^{-1})	0.80 [-0.04, 1.71]	-	-	-	0.01 [0.00, 0.01] ‡		-	-	-	0.04 [0.01, 0.09]	0.56 [0.06, 2.15]	0.828	0.163	11	3
	EP (g.day^{-1})	16.0 [11.6, 20.4]	-	-	-	0.23 [0.03, 0.42]*		-	-	-	1.76 [1.01, 3.03]	5.71 [3.10, 10.8]	0.835	0.162	17	6

† EI: standard errors imputed where missing, EP: standard errors presented in study, WN: meta-analysis weighted by estimate sample size because too few standard errors available, see Appendix 4.2.2 for details.

‡ Although marginally significant, divergent transitions when model ran so results not reliable

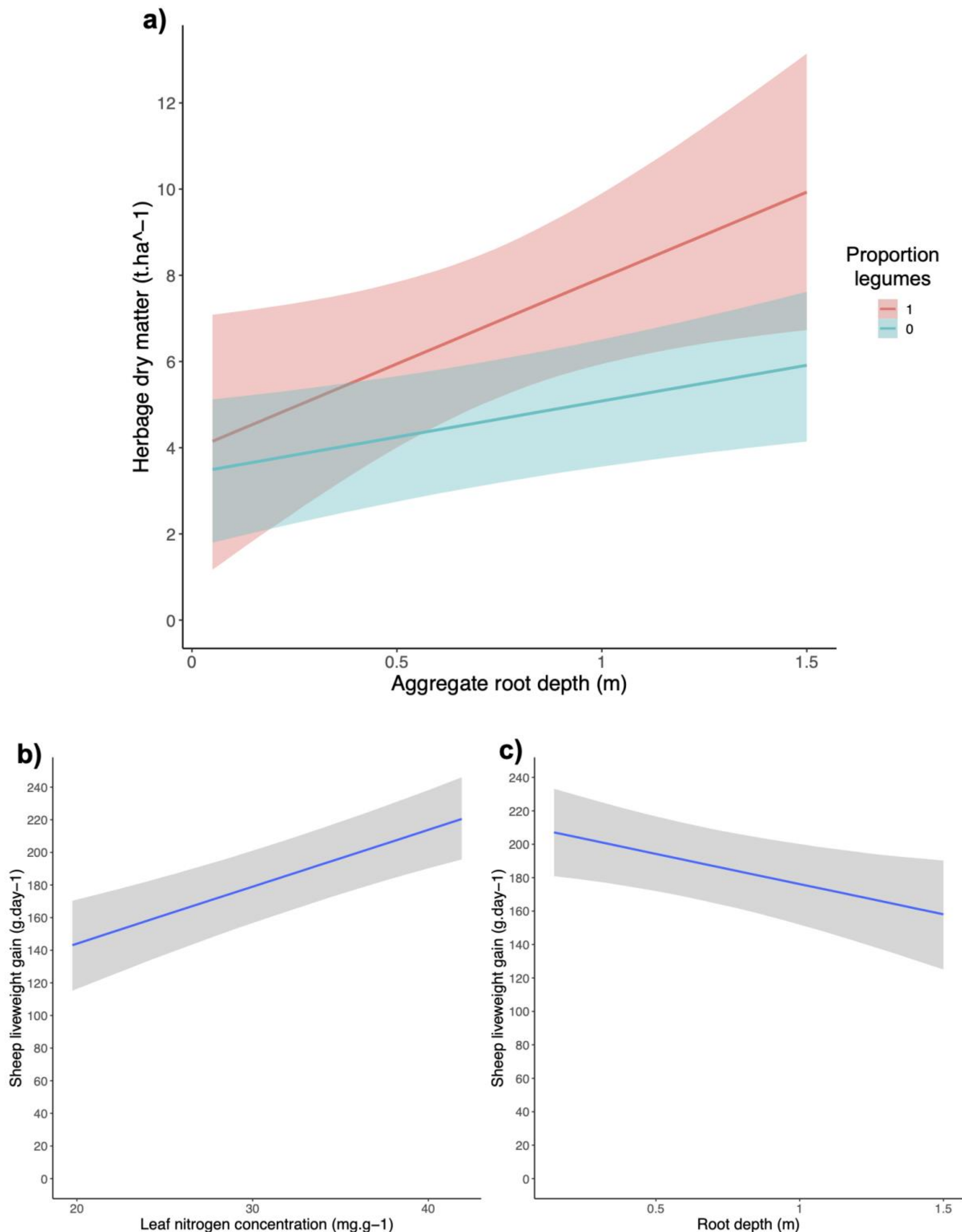

Figure 6.4. Productivity effects of herbal leys. Conditional effects of **a**) sward average root depth (m) and legume abundance on herbage dry matter production (DM, $t.ha^{-1}$), and **b**) leaf nitrogen concentration per leaf dry mass ($mg.g^{-1}$) and (**c**) sward average root depth (m) on sheep daily liveweight gain ($g.day^{-1}$). Error bars show 95% Credible Intervals.

Species evenness (inverse Simpson's diversity index) of the sward also positively predicts dry matter production, with an increase of 2.76 $t.ha^{-1}$, 95% CI [0.95, 4.56], between indices of 0 and 1. This aligns with evidence from plant biodiversity experiments of 'overyielding' in mixtures compared to monocultures in both experimental plots (Weisser et al., 2017, Tilman et al., 2001, Hector et al., 1999) and agricultural grasslands (Nyfeler et al., 2009, Finn et al., 2013), but was not robust to sensitivity analyses here (Table A4.10). We did not detect a significant increase in herbage production with higher sward species richness, 95% CI [-0.04, 0.29] (Table 6.4), which could be due to i) the high number of monoculture treatments in our dataset including particularly high-yielding species such as lucerne (Douglas, 1986), and ii) many of the studies in our database are of short duration, so may not have been exposed to the environmental stresses that result in mixes performing better on average (Sanderson et al., 2005). Herbage production is negatively related to absolute latitude (Table 6.4), as would be expected within temperate oceanic regions with shorter growing seasons and cooler temperatures further from the equator.

Livestock DLWG increased by 3.50 $g.day^{-1}$, 95% CI [2.17, 4.82] (Table 6.4, Fig 6.4b), for each milligram increase in leaf nitrogen content per gram of leaf dry mass ($mg.g^{-1}$). This is expected given dietary crude protein content boosts animal growth rates (Cranston et al., 2015, Luscher et al., 2014), although i) leaf nitrogen concentration analysis is not a direct proxy of forage complete protein content, ii) animal performance is influenced by protein that reaches the small intestine for absorption (i.e. protected from degradation in the rumen) rather than simply ingested

protein, and iii) forage needs to contain the correct protein:carbohydrate ratio to enable optimal animal performance. This positive relationship was also observed in the limited data available on wool growth ($mg.cm^{-2}.day^{-1}$, $g.day^{-1}$, Table 6.4, Fig A4.2), potentially mediated by dietary essential amino acid availability (Barry, 1998). It is important to note that this result supports use of high leaf-nitrogen forages to promote livestock growth, rather than HL per se; some forage species monocultures that achieve the highest sheep DLWGs are already widespread in conventional sward mixes, e.g. white clover (Fig A4.3). DLWG decreased in deeper rooting swards by 36.3 $g.day^{-1}$, 95% CI [-64.1, -7.62] (Table 6.4, Fig 6.4c), per metre of sward average rooting depth. This is arguably unexpected given the enhanced mineral content of some deep-rooted herb species (Li and Kemp, 2005, Stewart, 1996), but is potentially explained by the lower forage quality of some deeper rooting grasses such as cocksfoot (*D. glomerata*) compared with high-quality but shallow rooted species such as clovers (Fig A4.3). These effects of leaf N and root depth were robust to sensitivity analyses (Table A4.10).

Further, species richness and evenness did not appear to affect livestock growth rates (Table 6.4). Although the benefits of plant diversity to forage production may not be anticipated to translate directly to livestock DLWG, there are several reasons to expect species mixtures to deliver better animal performance than monocultures. Most forage species have disadvantages when sown in monoculture (Stewart, 1996, Burke et al., 2002) which can be mitigated when grown in mixtures, for example by providing a more optimal dietary carbohydrate to protein ratio or plants containing

CTs such as trefoils reducing instances of clover-induced bloat in livestock (Luscher et al., 2014). However, in well-designed seed mixes the benefits of such species complementarity are likely to saturate at a low total species richness which could explain why our results do not support hyper-diverse mixes strictly for improving livestock performance. Forage digestibility, as influenced by sward management such as grazing regime, likely masks any effect of species richness and evenness, and lower diversity swards are in general easier to manage to maintain digestibility. Indeed, improved milk yield when grazing diverse swards has been linked to higher palatability and therefore greater intake rather than higher forage quality per se (Jonker et al., 2019, Loza et al., 2021). Although highly diverse swards are widely promoted by RA practitioners, this is often to deliver multiple objectives which include increasing yield stability, promoting soil microbiological activity and building soil carbon (see Section 6.5.3) rather than further enhancing forage productivity or liveweight gains per se. The subset of our data that measured both livestock DLWG and herbage dry matter for the same treatments identified a negative relationship between these two outcomes; DLWG decreased by 4.62 $g.day^{-1}$ for every extra $t.ha^{-1}$ of dry matter production, 95% CI [-5.89, -3.35] (Table 6.4). Taken together, these results confirm the well-established notion that forage quality (for which we used leaf nitrogen content as a proxy) drives livestock growth when forage quantity (herbage dry matter) is not limiting. Finally, absolute Latitude positively predicts DLWG (Table 6.4). Although this could potentially be due to reduced animal heat stress in cooler regions, we restricted our meta-analyses to studies from temperate oceanic regions (Cfb, Köppen-Geiger classification) in an effort to control for the effect of climate on

productivity outcomes and this finding could be spurious given it was not supported in the EP and CA sensitivity analyses (Table A4.10).

We did not find a significant effect of leaf CT concentration ($mg.g^{-1}$ of leaf dry mass) on sheep DLWG. This relationship did not change when tannin action was inhibited through livestock treatment with polyethylene glycol (PEG) which bind CTs (Fig 6.5a, Table 6.5). However, CT concentration alone is known to be a poor indicator of bioactivity and we were unable to account for the molecular structure of CTs in different forage species which mediates their impact (Mueller-Harvey et al., 2019). Furthermore, we analysed CT data from eight species monocultures or mixtures, so other differences in composition, digestion or intake between these forages could mask any impact of tannins on livestock performance (Mueller-Harvey et al., 2019). Although the EP sensitivity analysis found that leaf CT concentration positively predicted DLWG (Table A4.11), we do not find mechanistic support for this in our dataset. CTs are expected to protect forage protein from rumen degradation thus increasing uptake in the small intestine (Luscher et al., 2014, Wilkins and Jones, 2000, Barry, 1998), but this has yet to be linked to improved animal growth rate (Mueller-Harvey et al., 2019) and leaf CT content did not have a significant moderating effect on the relationship between leaf nitrogen content and DLWG in our analysis (Fig 6.5b, Tables 6.5 & A4.11). This accords with recent empirical work which found that consumption of CT-rich forages simply shifted livestock N excretion from urine to faeces but did not increase animal retention (Grosse Brinkhaus et al., 2016, Azuhnwi et al., 2013). The expanding Credible Intervals in Fig 6.5b also

indicates that we have insufficient observations of high leaf CT contents in our dataset to identify this relationship, and therefore our result should be treated as absence of evidence rather than evidence of absence of an effect.

Table 6.5. Model estimates of sheep daily liveweight gain (DLWG, g.day^{-1}) and sheep faecal egg count (FEC, eggs.g-^{1}) for studies of herbal leys which measured either leaf condensed tannin concentration of treatment forages or sheep internal parasite burden. 95% Credible Intervals are given in brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis. Full model summary outputs presented in Appendix 4.2.3.1.

Outcome	Model†	Intercept	Tannin	PEG	Tannin *PEG	Leaf N	Tannin*leaf N	FEC	Wormer	Tannin*Wormer	Latitude	Standard deviation parameters		R^2		Number of	
												Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
DLWG (g.day^{-1})	EI	158 [120, 197]	0.74‡ [-0.38, 1.86]	-10.14 [-54.5, 32.4]	0.45 [-1.15, 2.06]	-	-	-	-	-	-28.1 [-55.3, -0.90]*	53.7 [39.9, 72.3]	63.1 [36.0, 101]	0.629	0.235	45	15
	EI	170 [110, 231]	1.41‡ [-1.94, 4.90]	-	-	7.73 [-9.64, 25.5]	0.57 [-0.46, 1.61]	-	-	-	-	52.9 [36.4, 77.3]	69.8 [37.2, 114]	0.645	0.119	32	13
	EI	184 [146, 222]	-	-	-	-	-	-0.04 [-0.05, -0.02]*	-	-	4.20 [-2.67, 11.0]	45.2 [36.6, 56.0]	70.2 [43.0, 109]	0.722	0.378	73	16
FEC (eggs.g^{-1})	WN	1300 [802, 1770]	1.89§ [0.35, 3.45]*	-	-	-	-	-	-818 [-928, -706]*	25.4 [17.8, 33.0]*	-4.19 [-80.6, 70.1]	397 [386, 409]	807 [529, 1290]	0.826	0.204	34	13

† EI: standard errors imputed where missing, WN: meta-analysis weighted by estimate sample size because too few standard errors available, see Appendix 4.2.2 for details.
‡ Tannin values measured in studies.
§ Tannin values from meta-estimate of data in (predominantly) other studies.

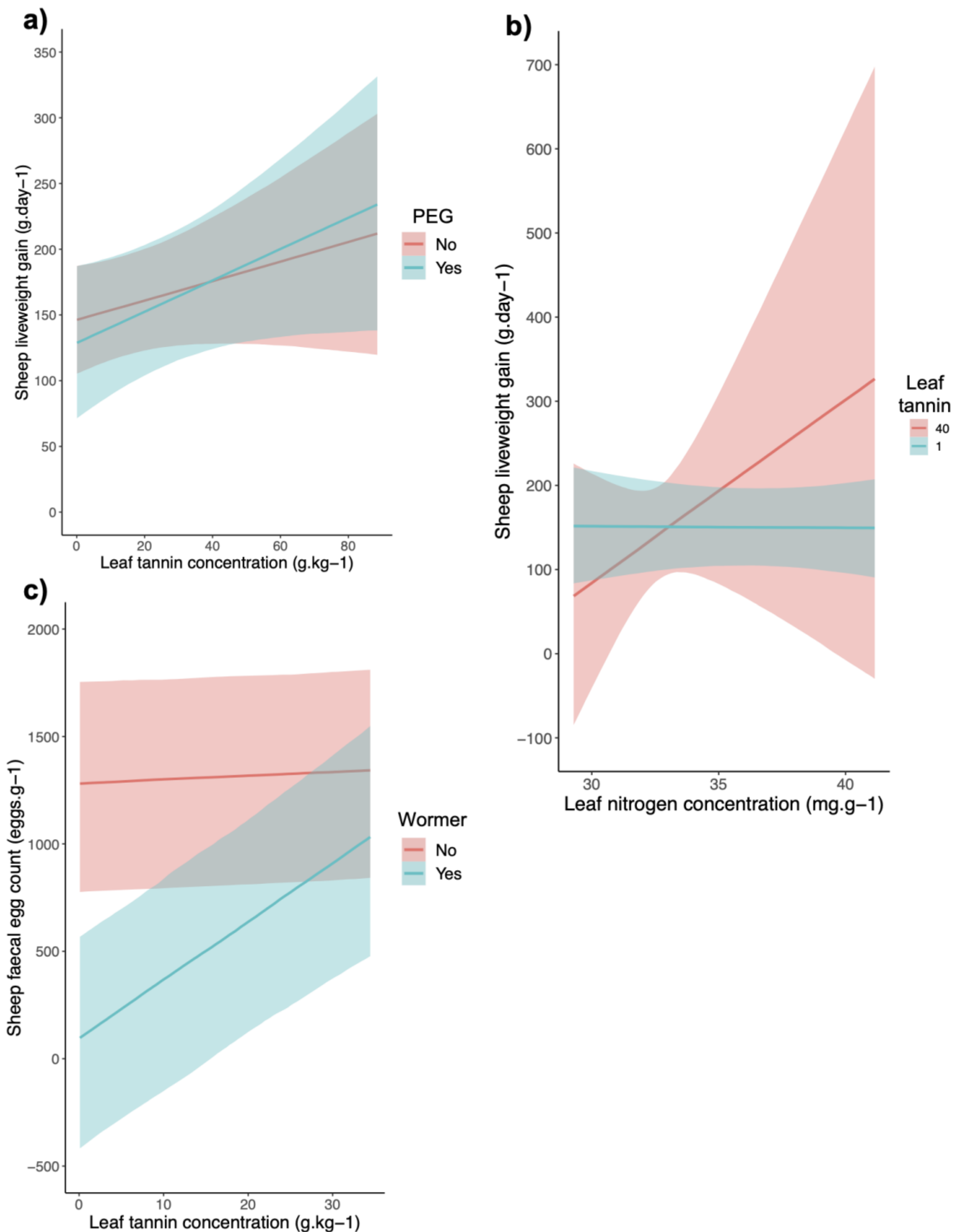

Figure 6.5. Sheep growth and internal parasite effects of leaf condensed tannins (CT). Conditional effects of **a**) interaction between leaf CT concentration per forage dry mass (g.kg^{-1}) and polyethylene glycol (PEG, inhibits tannins) treatment on sheep daily liveweight gain (g.day^{-1}), **b**) interaction between leaf nitrogen concentration per leaf dry mass (mg.g^{-1}) and leaf CT concentration per forage dry mass (g.kg^{-1}) on sheep daily liveweight gain (g.day^{-1}), and **c**) interaction between leaf CT concentration per forage dry mass (g.kg^{-1}) and anthelmintic treatment (wormer) on sheep daily liveweight gain (g.day^{-1}). Error bars show 95% Credible Intervals.

Regarding the impact of average leaf CT content (Table 6.2) on livestock internal parasite burdens, we identified a significant interaction between herbage CT content and wormer treatment (Table 6.5). If CTs in forage have anthelmintic properties then we would expect to find a negative effect of increased leaf tannin content on FEC, which would be attenuated when sheep are dosed with de-wormer. Our analysis in fact identified no effect of leaf CT content on FEC when no wormer treatment was applied, but positively predicted FEC when wormer was applied (Fig 6.5c). This unintuitive result suggests that tannins may be related to other factors not accounted for in our analysis which increase FEC count at higher leaf CT contents. When analysed separately, sheep FEC was negatively related to DLWG as expected, reducing livestock growth by 40 $g.day^{-1}$, 95% CI [-50, -20], per 1000 eggs per gram of faecal matter (Table 6.5). Although reduced intestinal worm burden on HL is frequently attributed to the anthelmintic properties of CT-rich herb species in the sward, other possible mechanisms include interrupting the parasites' life cycle by a combination of i) leaf shape and growth habitat of herbs, in addition to taller sward heights at grazing, impairing the ability of larvae to climb sufficiently far up forage to be ingested by sheep compared to short grass-majority swards, and ii) RG practices (frequently adopted on HL in order to preserve more sensitive sward components by allowing recovery time) preventing larvae hatched from eggs deposited in one grazing period surviving until the next grazing period to reach a new host.

We used trait data from the TRY database (Kattge et al., 2020) to estimate trait values for forage species and mixtures in our analysis. However, it is well-

established that many traits are to some extent plastic and thus differ depending on site-specific conditions (Fromm, 2019, Sultan, 2000). We were unable to verify the generalisability of trait values from this database to the study sites in our systematic review, nor do we account for the differences in trait values between naturally occurring wild-type varieties (potentially measured in TRY) versus agriculturally improved cultivars selected for specific properties (often sown in the agricultural research trials analysed here). However, given studies in our systematic review did not measure values for these traits (except for CTs, not available in TRY), this was a necessary approximation to test widely cited mechanisms for the potential of HL to increase productivity. Although trait values likely differ between study sites and vary across cultivars, we feel that the TRY database gives acceptable estimates of the relative magnitude of traits between species and thus argue that the overall trends identified by our analysis are valid. We also tested the sensitivity of our results to the quality of trait data available from TRY which preserved the findings discussed above (TSV, Table A4.10).

Aggregating traits across species present in a sward is arguably an oversimplification of the ecological dynamics that could affect productivity. For example, although increased rooting depth confers drought tolerance and greater access to nutrients, complementarity in rooting structures between sward components is also likely to be important. In addition, seed mixes, underpinning aggregated trait values for 95 observations of herbage dry matter and 23 observations of DLWG (Tables 6.4 & A4.10), provide only weak inference of i)

species abundance in the mature sward, particularly due to seed size, sowing method and management non-randomly influencing species establishment and persistence, ii) forage biomass available per species, and iii) forage consumed by livestock, particularly given livestock are known to selectively graze both species and plant components in mixtures. However, analyses that tested the sensitivity of our results to this trait aggregation process and use of seed mix data for weighting trait values supported our findings for DLWG and the influence of legumes on herbage dry matter production, although the positive effects of root depth and species evenness on herbage DM were not preserved (AV and SMV, Table A4.10). Finally, although trait or seed mix data was missing for some sward components, excluding these observations only affected our finding of species evenness promoting herbage DM production (MD, Table A4.10).

6.5.3. Soil carbon

Enhancing soil organic carbon (SOC) stocks is widely promoted as a key benefit of adopting RA (Moyer et al., 2020, Burgess et al., 2019, Newton et al., 2020). Regenerative practices in temperate arable systems have recently been demonstrated to increase SOC concentration without reducing crop yields (Jordon et al., 2022). However, our systematic review only identified two studies of SOC under RG and HL each (Table 6.2), which is insufficient for meta-analysis and is in line with the findings of Conant et al. (2017) and Byrnes et al. (2018) that there remains a paucity of evidence to assess the effect of these practices on SOC in temperate pastoral systems.

From the results of our systematic review, Díaz de Otálora et al. (2021) identified significantly higher carbon stocks in the top 10 cm of soil under 'regenerative' (1-2 days grazing, 24 days rest) compared to 'conventional' (6-10 days grazing, 15 days rest) RG after six years in Basque Country, Spain, while (Orgill et al., 2018) did not detect any difference in 0-30 cm SOC stocks under native pasture after five years of cell grazed vs set stocked in New South Wales, Australia. Potential mechanisms for RG to increase SOC stocks compared to continuous grazing include: i) rest periods which allow forage to accumulate and leaf photosynthetic area to increase will likely promote root growth (as plant belowground biomass is typically in proportion to aboveground biomass) and increase root exudates into the soil, promoting soil microbiological activity which may stabilise a portion of these organic inputs in soil aggregates, and ii) mob-style grazing systems which aim to allow substantial forage accumulation and then trample a proportion of this during short grazing events, resulting in a layer of dead and decomposing vegetation at the soil surface which may increase plant residue inputs to the soil (Jones and Donnelly, 2004, Eyles et al., 2015, Rumpel et al., 2015, Piñeiro et al., 2010). Despite being credible, these mechanisms have yet to be supported by empirical findings in temperate regions. A recent global meta-analysis found greater SOC under RG compared to continuous grazing in other climatic regions (Byrnes et al., 2018), whereas temperate studies of grazing systems typically find no effect on SOC (Techio Pereira et al., 2018). This could be due in part to the inherent difficulty of detecting small changes in SOC stocks when substantial heterogeneity exists in baseline soil properties both within

and between experimental pastures (Sanderman et al., 2015), and increased carbon inputs to soil not necessarily resulting in SOC accumulation, for example through concurrent changes in carbon stabilisation or decomposition (Eyles et al., 2015, Whitehead et al., 2018). In addition, there are several confounding factors which are possibly responsible for a disjoint between anecdotal practitioner reports of increased SOC following adoption of RG and existing empirical evidence, including: i) stocking density rather than grazing system (rotational vs continuous) per se impacting mechanisms for building SOC, ii) management intensity, which is typically higher under RG compared to simpler set-stocking, may lead to simultaneous adoption of other beneficial management practices which influence SOC, and iii) baseline, as previously degraded soils are likely to show improvements in SOC when improved management practices are adopted regardless of grazing system (Jones and Donnelly, 2004, Rumpel et al., 2015, Conant et al., 2017, Briske et al., 2008, Abdalla et al., 2018).

Regarding HL, the two studies identified by our systematic review (Cong et al., 2014, Savage et al., 2019) concur with findings from the Jena biodiversity experiment, field trials in the USA and a recent synthesis across biomes in China that plant species richness is positively related with increased SOC (Prommer et al., 2020, Skinner and Dell, 2016, Chen et al., 2018). This is likely due to higher levels of root exudation and reduced evaporation from the topsoil due to denser vegetation in diverse plant communities promoting metabolic activity of soil microorganisms (Lange et al., 2015). In addition to diversity generally, properties of certain plants typically included

in HL can specifically benefit soil carbon accumulation, including through i) enhanced rooting depth which delivers root exudates to lower soil horizons promoting microbial activity and soil aggregation, and therefore SOC stabilisation (Whitehead, 2020, Dodd et al., 2011), and ii) the presence of legumes which increase both below- and above-ground productivity through nitrogen fixation thus delivering more plant residue inputs to the soil, and increasing availability of N in the soil for humus formation (Rumpel et al., 2015, Conant et al., 2001, Luscher et al., 2014). Although HL typically require rejuvenation through reseeding every four or five years as the more sensitive or palatable species are lost from the mixture, this can be achieved by direct drilling approaches rather than cultivation, which risks degrading SOC by disrupting soil aggregates exposing the organic matter within these to microbial degradation. In addition, practices further along the regenerative ‘spectrum’ (Fig 6.1) would seek to create and maintain species-diverse permanent pastures through grazing management rather than reseeding or overseeding approaches.

6.5.4. Limitations and future directions

We provide an initial quantitative synthesis of the mechanisms by which regenerative grazing management claims to increase productivity. There was insufficient evidence to analyse the impact of these practices on milk production (Table 6.2), resulting in our findings predominantly applying to lamb and beef production systems rather than dairy, although inclusion of herbs in multispecies swards has been found to increase dairy cow milk yield in a recent meta-analysis (McCarthy et al., 2020). Although our analysis identifies several statistically significant relationships between quantitative

features of management interventions and productivity outcomes, we cannot demonstrate causation using our approach. It therefore remains possible that the relationships observed here could be mutually caused by an unidentified third variable (i.e. a confounder), but our results have value by indicating that mechanisms cited by proponents of RA at least predict productivity outcomes. Future work should seek to verify these mechanisms through detailed experimental manipulations, for example through factorial treatments of different rest periods and stocking densities in RG systems, or comparing HL sward mixes with multiple cultivars of the same forage species that differ in key traits of interest such as rooting depth.

However, there are several key differences between the management interventions analysed here and RA in practice, which highlight important caveats to the applicability of our findings. Firstly, studies in our systematic review typically implement *prescriptive* experimental treatments, which contrasts with more holistic and *adaptive* management of RA practitioners. This has been summarised in a rangeland context by Briske et al (2008): "Reduced flexibility in grazing experiments removes many sources of potential variation, but at the risk of becoming unrealistically abstracted from management applications. This is very likely the most serious limitation of the experimental data assessing the efficacy of rotational grazing." Future experimental work should compare prescriptive treatments with more adaptive management to see if this influences outcomes (Briske et al., 2011b), as has been done to some extent in North America (LaCanne and Lundgren, 2018, Rowntree et al., 2020). Secondly, there are likely to be differences in other

management practices and philosophy between the studies synthesised here and RA practitioners which are not included in our analyses and may influence productivity outcomes. Studies in our dataset frequently applied RG or HL treatments using a ‘conventional’ agriculture approach of soil tillage to reseed pastures, growing forage species monocultures, applying synthetic fertilisers, and focusing purely on herbage or stock production as outcomes, which would not be considered truly regenerative by some practitioners. Conversely, key management objectives in RA include promoting soil microbiological activity, restoring ecosystem functioning, and increasing system resilience, hence why actions such as maximising sward diversity may be prioritised even if this potentially offers limited or no direct livestock production benefit as found in our analysis. Thirdly, we were unable to consider the interaction between RG and HL, despite these clearly being non-independent (Fig 6.1). This was because no studies implemented both interventions factorially and few studies considered the impact of grazing management on sward diversity. Ironically, the one study which considered RG and HL in combination was excluded from our analysis because the interventions were confounded (Zaralis and Padel, 2019), yet this most closely approximates what RA would entail in practice. Future studies that compare ‘conventional’ with ‘regenerative’ management systems could help address this, either via experimental treatments or observations of practitioners’ farms. Finally, it is important to note that RA as implemented on temperate livestock farms may include other practices, in addition to those considered here, including silvopastoral agroforestry or integration of livestock into arable cropping rotations. Our results should therefore not be used without caveats when assessing the overall

impact of regenerative grazing. We are not claiming our results are universally generalisable, but that they are indicative of significant benefits.

On a related note, the results of meta-analyses such as this aim to identify general relationships across studies and therefore contexts. While this is useful for informing policymakers and identifying directions for future academic work, our results are not suitable for providing management recommendations to practitioners in their specific context, although we did restrict our systematic review to a temperate oceanic climate to maximise the generalisability of results within these regions. Furthermore, we do not account for the potential disadvantages of adopting these interventions in practice. For RG, these include costs of fencing and water provision infrastructure to divide existing fields into smaller paddocks for rotation. HL seed mixes can be expensive and risky to establish, and often contain species which are unsuited to winter grazing and require RG to ensure persistence, reducing farm-scale management flexibility. Future work should also consider the drivers and barriers for farmers to adopt these practices, which may mitigate any potential productivity benefits. In addition, there are other potential benefits of transitioning to RA in pastoral systems, including enhanced biodiversity and improvements in water quality and water flow regulation, which we do not consider here but should be accounted for in future work to assess the overall environmental impact of regenerative grazing practices.

6.6. Conclusions

We provide empirical support for mechanisms by which rotational grazing and increasing sward diversity to include perennial forbs (i.e. herbal leys) can increase forage production and sheep and cattle growth rates in temperate oceanic regions. We find that increasing the proportion of the grazing season that a pasture is rested promotes herbage DM production and livestock DLWG (at higher stocking densities). Inclusion of deep-rooted species and legumes into the sward, and higher species evenness, enhances DM production. Higher forage nitrogen concentration (a proxy for protein content) promotes livestock growth rates. The currently available evidence does not support assertions that tannins promote livestock growth rate, enable better dietary protein utilisation or reduce internal parasite burdens. Further work is required to determine the influence of forage CT content on livestock performance. Although additional research is necessary to verify the mechanisms investigated here beyond predictive relationships, and there remains a disjoint between experimental treatments in published studies and actions of RA practitioners, our results suggest that further adoption of these RA practices on temperate grazing land has potential to reduce the greenhouse gas emissions associated with ruminant farming by increasing livestock productivity.

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Chapter 7. Advantages, disadvantages, and reasons for non-adoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms

7.1. Summary

This final data chapter details the work I undertook to address the third aim of my thesis namely determining the appeal of RA practices to land managers. It describes the output from my semi-structured interviews with English sheep and beef cattle farmers and industry representatives to assess the likely appeal of implementing four RA practices considered in previous chapters (rotational grazing, herbal leys, trees on farms and ley-arable rotations). The interview questions were devised to determine the perceived advantages and disadvantages of these practices. Furthermore, output from these interviews enabled me to identify key reasons that farmers choose not to implement RA practices on their land. These reasons included initial capital outlay, incompatibility with their current farming objectives, and the risk that adopting a new approach would not deliver the desired benefits. From this work I conclude that despite the emerging scientific evidence base that some RA practices may successfully enhance soil carbon and farm productivity, their uptake may be limited on working farms. This important finding needs to be taken into consideration when proposing the implementation of RA land management practices as key components of government policies for climate change mitigation and sustainable environments.

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Advantages, disadvantages, and reasons for non-adoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms

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7.2. Abstract

Adoption of rotational grazing or multi-species herbal leys, planting trees and integrating livestock into arable rotations can increase agricultural productivity and carbon storage on temperate ruminant livestock farms. However, farmers frequently have rational reasons for not adopting seemingly beneficial management practices. Here, we conduct semi-structured interviews with sheep and beef cattle farmers and industry representatives in England, to determine the advantages, disadvantages and reasons for non-adoption of these four management practices. We find key reasons that farmers rationally do not adopt these practices include capital outlay, incompatibility with farming objectives, and the risk that desired benefits are not delivered.

7.3. Introduction

The environmental sustainability of food production needs to increase to address the twin challenges of climate change and biodiversity loss. This issue is particularly acute for ruminant livestock farms, including sheep and beef cattle enterprises in the UK, which are associated with high greenhouse gas emissions from enteric fermentation along with other environmental impacts including reduced water quality and increased flood hazard (Gerber et al., 2013, Bilotta et al., 2007, Marshall et al., 2014). Measures that improve the productivity of these farms can reduce the environmental impact per unit of food produced (Herrero et al., 2016, Hristov et al., 2013). In addition, the typically more marginal farmland that these enterprises are located on is increasingly attractive to policy makers for land-based carbon sequestration as part of national climate change mitigation strategies, such as the UK's target of net zero emissions by 2050 (Climate Change Committee, 2020).

Measures that improve sheep and cattle productivity and/or increase farm carbon stocks include rotational grazing practices, incorporation of perennial forbs into multi-species swards (also known as herbal leys), integrating trees onto farms, and including a grass-based ley phase in arable rotations (Table 7.1, and citations therein). These practices are currently supported to some extent under existing English farm support schemes (Table 7.1), and are likely to form key components of England's future Environmental Land Management schemes (Defra, 2021b, Defra, 2021a). Combinations of these practices are simultaneously gaining interest from some land managers, policy makers and large corporations as part of a

Regenerative Agriculture approach (Giller et al., 2021, Gosnell et al., 2019), with private incentives and markets emerging to promote adoption of this management paradigm e.g. (Elliott et al., 2022). However, although the theoretical productivity gains or carbon sequestration potential of these changes in land management practices have been estimated (Pent, 2020, Torralba et al., 2016, McDonald et al., 2019, McCarthy et al., 2020, Mayer et al., 2022, Byrnes et al., 2018, Phukubye et al., 2022), this does not account for the appeal of these measures to land managers or the likelihood of adoption.

Table 7.1. Regenerative Agriculture practices applicable to English sheep and beef livestock farms investigated here.

Interventions	Definition	Synonyms	Selected theoretical advantages	Current government support (England)
Rotational grazing	"Movement of livestock between two or more subunits of pasture such that alternating periods of grazing and no grazing (rest) occur within a single growing season" (Briske et al., 2011)	Mob grazing, cell grazing, paddock grazing, controlled grazing, holistic planned grazing, adaptive multi-paddock grazing, strip grazing, precision grazing	Enhanced grass growth leading to improved livestock growth rates and potential for higher pasture carrying capacity (Jordon et al., 2022, McDonald et al., 2019)	Farming Equipment and Technology Fund electric fencing package (Rural Payments Agency, 2021)
Herbal leys	Intentional incorporation of perennial herbs and legumes into pasture swards, in addition to grasses and clovers, either through sowing seeds or creating conditions for these to persist/re-establish naturally (Jordon et al., 2022)	Multi-species leys, diverse swards	Enhanced sward diversity increases pasture productivity and resilience, inclusion of legumes build fertility through N fixation, deeper rooting species incur drought tolerance, plant trace mineral and secondary metabolite content improve livestock health (Jordon et al., 2022, McCarthy et al., 2020)	Countryside Stewardship option GS4 (Rural Payments Agency and Natural England, 2015a); Sustainable Farming Incentive grassland soils standard (Defra, 2021b)
Trees on farms	"Incorporation of trees into farming systems" (Gordon et al., 2018)	Agroforestry, silvopasture, farm woodland, shelterbelts, hedgerows	Reduced livestock heat and cold stress from shelter and shade, increased combined production for given land area, increased farm carbon storage (Jordon et al., 2020, Torralba et al., 2016, Pent, 2020, Mayer et al., 2022)	England Woodland Creation Offer (Forestry Commission, 2021); Countryside Stewardship (Rural Payments Agency, 2020)
Ley-arable	Temporary grass-based ley included for one or multiple consecutive years within arable rotation (Lemaire et al., 2015)	Integrated crop-livestock, mixed farming	Ley phase builds fertility for following arable cash crops, breaks arable weed lifecycles, and provides high-quality livestock forage (Elliot, 1908, Turner, 1951, Stapledon and Davies, 1948, Martin et al., 2020). Arable phase can provide livestock feed and bedding.	Countryside Stewardship option SW7 (Rural Payments Agency and Natural England, 2015b)

There is a substantial body of literature that seeks to understand and predict adoption of management practices by farmers. Many of these take a behavioural approach, focusing on “the motives, values and attitudes that determine the decision-making processes of individual farmers” (Morris and Potter, 1995, Burton, 2004a), often developing or applying models of farmer behaviour, see (Journeaux et al., 2018, Rose et al., 2018a). However, studies of farmer adoption of agricultural innovations and new technologies often implicitly assume that adoption is beneficial, and these benefits will be equally realised by all farmers (Vanclay and Lawrence, 1994), which may not account for the context-specific nature of farmer decision making (Journeaux et al., 2018). Moreover, where innovations are incompatible with existing, already successful, farmer workflows, this can lead to characterisation of some farmers as problem ‘non-adopters’, instead of recognising the limitations of an innovation (Rose et al., 2018b, Vanclay and Lawrence, 1994). Cognitive and behavioural models also tend to centre on the individual, which can miss “structural economic, environmental and social factors which affect an individual’s ability to change behaviour” (Journeaux et al., 2018), unless these are explicitly accounted for as in the Theory of Planned Behaviour. These, along with other factors, can result in farmers having a rational basis for non-adoption of management interventions, which have been categorised by Vanclay and Lawrence (1994) as: complexity of intervention, inability to trial or partially adopt, incompatibility with farm and personal objectives, loss of flexibility, risk of failure, conflicting information regarding benefits, cost of implementation, infrastructure requirements, and limited economic benefit. The four interventions under consideration here (Table 7.1) are already adopted to

some extent on English sheep and beef cattle farms. However, the prevalence and nature of such rational reasons for non-adoption needs to be understood, in order to determine the extent to which increased uptake for improved farm productivity or climate change mitigation is likely achievable in practice.

Here, we investigate the advantages and disadvantages of four Regenerative Agriculture practices applicable to sheep and beef cattle farms in England, UK. We conduct semi-structured interviews with national industry representatives, and farmers in two case study regions (Northumberland and Devon), to ascertain their views on rotational grazing, use of perennial forbs in multi-species swards (herbal leys), integrating trees onto farms, and incorporating livestock into arable rotations (ley-arable rotations) (Table 7.1). In addition to further understanding the benefits and downsides of these emerging management practices from farmers' perspectives, we aim to provide a preliminary indication of where rational reasons for non-adoption may exist and the aspects of the management practices or farmers' context that influences this. Although these practices have theoretical advantages including increasing carbon storage (i.e. sequestration) on livestock farms, our objective is to help inform the extent to which further adoption may be attainable in practice.

7.4. Methods

We used an inductive grounded-theory approach (Wengraf, 2001). Interviewees were non-randomly selected and initially contacted through the existing relationships

and professional networks of the study authors. The lead author conducted semi-structured interviews with 12 respondents in total; four each of industry representatives and farmers from the two case study regions (see Tables A5.1-4 for a summary of interviewee responses). We chose to include sheep and beef cattle farming industry representatives and farm advisors in our sampling as they can be well placed to provide a breadth of perspective across multiple contexts regarding the activities and views of the farmers they represent or work with (Mills et al., 2020). The farmer case study areas (mid Northumberland and west Devon) were not intended to be representative of the whole of the UK but were selected as illustrative of some beef cattle and sheep farming regions in England.

Interview questions were trialled on three social science researchers and non-participating farmers with oral feedback to ensure questions were clear, understandable, and likely to elicit informative responses that could be further probed. Respondents were provided with a Participant Information Sheet on first contact and informed consent was received through signing a written form before the interview commenced. Industry representative and farmer advisor interviews were conducted over Microsoft Teams video call in September 2021. They were asked to list all advantages and disadvantages of each practice based on conversations with or observations of their farming members/clients. They were also asked for their own views on the barriers to wider adoption of these practices and possible interventions (e.g. dissemination of advice, financial incentives) that could help overcome these. Advantages and disadvantages of each intervention identified by these respondents

were recorded so that farmers' extent of agreement with these could be explored in later interviews, which took place in late November (west Devon) and early December (mid Northumberland). Farmers were visited on farm and interviews conducted face-to-face in the farmhouse, with family members present in six out of eight cases. Where family members made contributions to the discussion of RA practices, these were included in the interview transcript, given the known importance of family influences on farm decision making (Wynne-Jones, 2013). The interviewer (MWJ) explained his background in sheep and beef cattle farming and outlined his other research interests, in order to build rapport with the interviewee and put them at ease. Practices were discussed in turn, with farmers first asked whether they adopted these or not, with a different phrasing of questions used depending on response to this, to discuss their perceptions of the advantages and disadvantages to each practice, and ideal policies or incentives that would help mitigate any disadvantages. A series of close ended multiple-choice questions were also asked at the end of the interview to gather participant meta-data.

Interview data were collected via audio recordings. These were transcribed in NVivo Transcription with manual proof checking. Transcripts were analysed in NVivo, with theme-based coding using well-established methods (Ryan and Bernard, 2016) to identify advantages, disadvantages and reasons for non-adoption of each practice.

Three national industry representatives for paid membership organisations and one farm advisor were interviewed (referred to collectively as 'industry representatives'

throughout). Of these, all bar one were also active farmers. There was a balanced mix of expertise in sheep and beef cattle enterprises and respondent ages (Fig A5.1), with all respondents having spent the majority of their working life in the agricultural sector. Of the farmers interviewed, all were (one of) the primary decision makers in a family business. Seven out of eight were owner-occupiers, although three of these also rented additional land on Farm Business Tenancies and/or Agriculture Holdings Act 'secure' tenancies. Land quality ranged from non-LFA (less favoured areas) to Moorland Severely Disadvantaged. All bar one were in agri-environmental or stewardship schemes. All had beef enterprises, and six of the eight also farmed sheep (Fig A5.2). Farmers interviewed relied on a variety of sources for new information, with the agricultural press, farm vets, peer-to-peer networks (predominantly paid membership industry organisations) and social media all seen as important (Fig A5.3).

7.5. Results and Discussion

7.5.1. Practice advantages and disadvantages

7.5.1.1. Rotational grazing

Rotational grazing (RG) was widely perceived to benefit forage production and livestock performance compared to continuous grazing (also known as set stocking). Improved grass productivity or growth rate was the most frequently cited advantage across respondents (Table A5.1), aligning with findings from a farmer survey in the USA (Wang et al., 2021) and mechanistic and empirical expectations that rest

periods enable overall greater herbage dry matter production (Jordon et al., 2022, Voisin, 1959).

"You undoubtedly grow more grass." Industry rep 1

Industry representatives and adopting farmers also identified further aspects of improvement in forage production including enhanced quality, utilisation and recovery rates post-grazing, in addition to creating a forage reserve which could act as a drought buffer (Table A5.1). Improved forage production was linked to better livestock performance, again only by industry reps and adopters of RG, implying that these benefits are potentially harder to recognise prior to adoption or receive less publicity. It was also found in the USA that benefits of RG are recognised to a greater extent by adopters than non-adopters (Wang et al., 2021). Although improvements in livestock performance in RG are primarily driven by improved forage production and quality (Jordon et al., 2022), one industry representative highlighted that mis-managed rotational grazing can result in compromised forage quality and therefore impair livestock performance, for example if livestock are not moved frequently enough so are grazing increasingly low-quality residuals.

The two key disadvantages of RG are infrastructure requirements (extra permanent or electric fencing to subdivide existing fields into smaller paddocks and supplying water to these) and labour (to erect fences and move stock), identified by industry representatives and adopting and non-adopting farmers (Table A5.1). This matches results of farmer surveys conducted in the USA (Wang et al., 2020), in particular the additive increase in labour requirements with RG intensity (Gillespie et al., 2008,

Gurda et al., 2018, Winsten et al., 2010). A further limitation was the risk of poaching caused by high stocking densities on small paddocks in wet conditions, a factor not identified by industry representatives.

"When you see these strips [grazed] fields, and I've been past them after a wet day… and you see, it just looks like a quagmire. So I don't know if there's any benefit when I see that, do you know what I mean." – Northumberland farmer 2

Some non-adopting farmers also indicated that they were not aware or unconvinced of the benefits of RG, as has been found in the USA (Wang et al., 2021).

"The grass will grow a certain amount a year." – Devon farmer 4

"I don't know. Um, I'm not really sure, is it [RG] a benefit...?" Northumberland farmer 2

7.5.1.2. Herbal leys

Improved livestock performance was cited as an advantage by all farmers who use herbal leys (HL), and by two out of three non-adopters (Table A5.2). This corresponds with a previous study in southwest England which found that increased liveweight gain was a driver for adoption of white clover (McKemey and Yates, 2003). Improved livestock growth or finishing rates were often linked by respondents to the higher protein content of forage due to the presence of legumes in the sward, as has recently been demonstrated by meta-analysis (Jordon et al., 2022). However,

several farmers highlighted the potential for reduced palatability if the sward is allowed to become overgrown, particularly if chicory (*C. intybus*) is present and bolts, with one industry representative linking this risk of lost palatability and quality with potentially impaired livestock performance.

"You've got to make sure that you eat it. You can't let it get overgrown… Because actually, once it's reached a certain stage, you've got to leave it and cut it, because it becomes pretty unpalatable sometimes." Devon farmer 2

In contrast to McKemey and Yates (2003), no respondents identified reduced concentrate use as an advantage of adopting HLs. Although there was recognition that including nitrogen-fixing legumes in the sward may benefit forage production and/or reduce fertiliser use, non-adopting farmers raised concerns that HL may not match the yields of ryegrass-dominated grass-clover leys (Table A5.2), with this uncertainty appearing to constrain uptake in some cases (see Section 3.2.1).

"Yield, fear of the unknown. I think a lot of that, a lot of people don't like change. The unknown." – Devon farmer 4

Improved mineral or trace element content of forage plus drought resistance, conferred by increased diversity and depth of rooting structures in HLs, were identified by adopting farmers and industry representatives, in agreement with a survey of Danish organic dairy farmers regarding including herbs in pastures (Smidt

and Brimer, 2005). Although potential anthelmintic properties of HLs were identified by three out of four industry representatives, this was only mentioned by one farmer (non-adopter), suggesting that this well-publicised benefit of HLs may not be experienced in practice, in contrast to Smidt and Brimer (2005) who found this as a reason for including chicory in pastures.

"We know that it does have an impact, but it also means that if we have a faecal egg count burden in a lamb and we know from live weight gain it's not doing [growing well], we still need to worm it." Industry rep 3

The most widely cited disadvantage of HLs is the difficulty of controlling broadleaved pasture weeds (Table A5.2), previously identified as a barrier to white clover adoption in southwest England (McKemey and Yates, 2003). Available pasture herbicides are only safe to use on grasses, and are non-selective across both desirable broadleaf species (e.g. clovers, chicory, plantain) and weeds (e.g. docks, nettles, thistles). The cost of reseeding in general and HL seed mixes in particular was raised more by industry representatives than farmers, although all farmers that adopted HLs raised concerns about variable establishment and retention of all components sown in HL mixes, leading to one industry rep to question the cost-effectiveness of sowing expensive but poorly retained mixes.

"So that's reality is that people… a lot of money is being paid for mixtures, that you could have just put in a simpler one and it's still the same, having the same impact a year later." Industry rep 3

Indeed, farmers frequently recognised that some species in HL mixes are unsuited to their land or climate, or that herbs in the mix may be unable to compete with the grasses, which could both explain poor retention. This contrasts with results from Denmark where establishment of herbs was found to be good on organic dairy farms (Smidt and Brimer, 2005). Further, some respondents felt that HLs in general were unnecessary, due to the ability to achieve similar or greater benefits by focusing purely on grass-clover mixes (perennial ryegrass, timothy, cocksfoot, and white and red clover).

"I've tried to really put a lot of clover into the sward. I always ask for more clover. When we're sowing the ordinary medium to long term leys, always have a higher clover content. And then we'll oversow with clover or stitch it in sometimes as well, as an alternative to herbal grazing, the herbal mixtures. And so, because I think that the clover is, for me is probably more important than herbal." Northumberland farmer 4

7.5.1.3. Trees on farms

All farmers interviewed identified increased shelter and shade for livestock as a benefit of integrating trees onto their farms (Table A5.3), in agreement with previous UK studies (Lawrence and Dandy, 2014) and found by a recent systematic map to be a clear benefit to farmers in temperate regions (Jordon et al., 2020). Although this

had been a reason for many farmers (seven out of the eight interviewed) to increase tree and/or hedge cover on their farms, the reluctance of the non-adopting farmer to plant trees and some adopters to plant more was due to the feeling that the farm already had sufficient shelter, so no further trees were required, or that all land deemed 'suitable' for trees (i.e. areas that are unproductive, marginal or difficult to farm) had already been planted.

"I'm not sure if, you know, when we've got sort of ten percent of the farm under trees anyway, that's, I think in an awful lot of cases, most of the land that I would feel should be under trees is under trees. To plant any more would be taking away what I would call decent, the better productive land. And then you take the balance out of the farming business. So it's a bit of a mixed bag. Yes, I'd like to plant where appropriate, but not just for the sake of it." – Devon farmer 2

Nevertheless, where marginal or unproductive land was available, planting trees represented a good use of this to some farmers. This was identified by an industry representative as potentially representing an attitude shift, although the non-adopting farmer noted that even marginal or less productive areas were still grazeable and saw a clear opportunity cost in terms of reduced stock carrying capacity if they were to plant these parts of their farm with trees.

"Where you've got a bad bit of a field, people are now happy to plant trees in it, whereas 10 or 15 years ago they were just trying to make it better." – Interview rep 4

Although previous reviews have found little interest from UK land owners in creating new woodlands (Lawrence and Dandy, 2014), more recent surveys indicate that attitudes could be changing (Hemery et al., 2020, Royal Forestry Society, 2020) and our study identifies significant *interest* in planting trees but over a small *extent* of a holding. Equally, it could be that the farm types interviewed here are particularly open to planting trees due to the relative compatibility with their existing farming system (i.e. grazed livestock) (Wynne-Jones, 2013).

Some farmers also referenced the cultural value of restoring tree cover and hedgerows, particularly in Devon where hedged field boundaries are an iconic part of the landscape. This has similarities to the findings of Lawrence and Dandy (2014) that maintaining landscape features is often given as a reason for woodland management, and accords with the results of Rois-Díaz et al. (2017) that a key driver for adopting agroforestry in Europe was tradition linked to culture. Lawrence and Dandy (2014) identify benefits to wildlife or biodiversity as the most common or primary objective of woodland creation and management in the UK, and while this wasn’t the case here (shelter and shade were identified by all respondents), biodiversity was mentioned as an advantage by five out of seven adopting farmers. Planting trees and hedges on farms was also seen to improve sporting value through providing cover for gamebirds, stabilise soil at risk of erosion, and provide an opportunity to achieve other objectives as co-benefits of planting grants such as sub-

dividing fields for rotational grazing, improving farm biosecurity at boundaries with neighbours, and fencing off water courses.

We identified nuanced responses regarding the impact of tree planting on farm economics. Three farmers felt that trees could in the future provide a diversified source of income to the farm business, both through the potential to harvest food from fruit and nut trees, and through enabling access to future farming support schemes. This contrasts with agroforestry across Europe, where diversification of products was found to be a key driver for adoption (Rois-Díaz et al., 2017), whereas in our study it was only mentioned once, potentially because such systems are relatively novel in the UK compared to other parts of Europe.

"If we're going down in agroforestry route where you would do it in field, I would be keen to look for something that was potentially another source of income, whether that's an orchard or whether something, you know, I haven't quite worked out what it is, whether it's hazelnuts, walnuts, orchard or something like that, it'd be interesting to see what, you know, rather than just planting trees for the sake of it." – Devon farmer 1

"I think if we want to earn any money, take any money out, we're going to have to do these sorts of things. That's the motivation, earning an income from the farm. And if it pays to… I don't think I'd take out any, I'm not one for taking out good land to put into trees." –

Northumberland farmer 4

However, there was also a perception that food production was more profitable than planting trees (Hardaker, 2018, Lawrence and Dandy, 2014), particularly on more productive areas of the farm (see above). Respondents expressed frustration that grant support is i) insufficient to incentivise further uptake, ii) too restrictive in species required to be planted, and iii) not available for the small-scale planting that most farmers are interested in doing,

"Its all money. That's all it is. I'm sure lots of farmers would have corners to plant they'd plant up, if they were paid the right amount to do it. There's got to be an awful, awful lot more flexibility from government really." – Northumberland farmer 4

Although this accords with existing evidence that woodland creation grants are inadequate and overly bureaucratic, complex and changeable (Jordon and Wentworth, 2021, Hardaker, 2018, Lawrence and Dandy, 2014) and we did find some suggestion that increased payment rates could potentially motivate further uptake (*"Well, if there'd been more money we might have planted a bit more" – Northumberland farmer 1*), it is also well established the UK land managers are not primarily motivated by making money when planting trees (Lawrence and Dandy, 2014). Production or value of timber was not mentioned by any respondents, according with the findings of Lawrence and Dandy (2014) that timber production is "consistently rated low" as an objective for woodland management, in contrast to

biodiversity conservation, shelter, shooting and other amenities or leisure activities identified as more important by woodland owners.

A repeated theme, as seen in the quotes above, was a reluctance to plant trees “for the sake of it” or to plant on a farm’s more productive land. This aligns with widespread evidence of a cultural perception among UK farmers that agricultural land is ‘too good’ for trees (Hardaker, 2018, Lawrence and Dandy, 2014) and that land that can be farmed should (Burton, 2004b), plus evidence from Europe that where land is highly valuable and productive, farmers prefer to focus on agriculture and see agroforestry as having an opportunity cost (Rois-Díaz et al., 2017). This linked to a broader sentiment expressed by some farmers that an over-emphasis on tree planting would negatively impact national food security and their livelihood as farmers, particularly emotive given many farmers’ strong identity as food producers (Jordon and Wentworth, 2021, Burton, 2004b, Wynne-Jones, 2013).

“If they plant trees all round here there's going to be no need for us to exist anymore. So I don't know what's going to happen to me. What am I going to do? Is the government going to supply me with a job? I don't know what will happen. But. I think that I just think it's a bit short-sighted.” – Northumberland farmer 2

“What they [policymakers] want is everything bar food. Isn't it? They just want [expletive]. Planting trees.” – Northumberland farmer 1

Relatedly, although carbon sequestration was mentioned as a benefit of increasing farm tree cover by two farmers, one farmer identified the growing carbon offset market as their biggest concern around the current political focus on tree planting in the UK.

"And one of our biggest fears is businesses coming in and buying up land and using us as carbon offsets. And that can't then... No farmer in the future, a genuine farmer, will be able to get back into it and buy it back. And once that sort of land is gone... And then we will not have any food security. I think, I think other businesses… I think you have to think, if there was an ideal rule it would be that to purchase land you have to be a genuine farmer, not a businessman." – Devon farmer 4

If trees are planted within fields rather than at field edges, disadvantages include the inconvenience to farm operations, also found to be a barrier for adopting agroforestry in Europe (Rois-Díaz et al., 2017), risk of blocking field drains, loss of production directly under trees due to shading, competition for nutrients in the surrounding soil, and the perception that farming is more profitable (Table A5.3). Although the permanence of land use change following tree planting was raised as an issue (Lawrence and Dandy, 2014), one farmer noted that this didn't matter as the land they had planted was so marginal they wouldn't want to farm it anyway. The potential loss of the Agricultural Property Relief inheritance tax break from planting trees on farmland was also raised, which has previously been highlighted for review

by the UK Climate Change Committee to ensure no tax disadvantage from woodland creation (Climate Change Committee, 2020).

7.5.1.4. Ley-arable

There are two possible aspects of engagement by English livestock farmers with ley-arable rotations and integrating livestock into arable systems; they can either grow arable crops on their own farm in rotation with temporary grass leys (mixed farming) or send livestock to temporary grazing on arable farms either on short term leys or overwinter fodder or cover crops (sending stock to arable). Five of the eight farmers interviewed currently practice or had practiced mixed farming, but none sent stock to arable.

The most cited benefits of mixed farming were improved soil health, fertility and crop yield compared to continuous arable cropping, identified by industry representatives and both adopting and non-adopting farmers (Table A5.4) and matching previous studies and reviews (Cullen and Hill, 2006, Schut et al., 2021, Bell et al., 2014, Smith et al., 2007, Kragt et al., 2017). Improved soil health was linked to increased soil organic matter by industry representatives but not by farmers, suggesting a potential disconnect between broader industry and policy interest in restoring soil organic matter for carbon sequestration (Smith et al., 2007) versus the more practical and immediate concerns of farmers.

The role of temporary grass leys in helping to manage arable weeds, particularly for which herbicide resistance is increasing such as blackgrass (*A. myosuroides*), was also widely recognised by respondents (Table A5.4) and is a well-established benefit of integrating livestock into arable (Cullen and Hill, 2006, Schut et al., 2021, Bell et al., 2014, Bell and Moore, 2012). Indeed, weed management benefits of mixed farming is thought to be one reason why this practice has persisted in Australia rather than simplifying to continuous cropping systems which are more profitable in the short term (Kirkegaard et al., 2014). Interestingly, there was also a perception that ley-arable rotations provided opportunities for *grassland* weed control and may improve some aspects of grassland soil health, i.e. some benefits apply both to the arable and grassland phases of the rotation. Furthermore, one mixed farming adopter grazed their autumn-sown cereal crops during the winter with sheep, finding that this helped reduce weeds and built fertility.

"It tillers a lot better. Like I say, we'll save a herbicide and they're putting manure back on it. So I, at a guess, I would say 10 units of nitrogen, it would save us. But like I say, the agronomist hates it. We just don't take any notice of him." – Devon farmer 4

Although currently not widely adopted in the UK, over-winter grazing of cereals is increasingly popular on mixed farms in Australia, where benefits include increased productivity through the ability to rest pastures overwinter (Bell et al., 2014).

Farmers widely recognised the benefit of producing their own cereal for livestock feed and straw for bedding, i.e. providing production complementarity (Bell and Moore, 2012) or economies of scope (Schut et al., 2021). Respondents perceived this as a way of reducing costs and dependence on bought-in inputs, potentially improving business resilience to the upcoming removal of the Basic Payment Scheme in England. Mixed farming in Australia has been demonstrated to mitigate financial risk from fluctuations in livestock vs arable income sources (Bell and Moore, 2012), although this could be less applicable here where most adopting farmers used a significant portion of home-grown cereal for their own livestock feed.

Conversely, mixed farming can struggle to be cost effective, particularly when done at a small scale and in years when cereal grains are cheap to buy due to low commodity prices (although not currently the case). This was cited as a key disadvantage and reason some farmers interviewed had stopped mixed farming in favour of grass-only. Higher costs and being uneconomical without subsidies have similarly been identified as barriers to the inclusion of legumes in arable rotations in Europe (Mills et al., 2020), although this is a different practice to ley-arable. Further, arable machinery and implements are increasingly expensive and therefore unviable to purchase for small cropping areas. Cost of adoption, inefficient resource allocation and inability to access economies of scale are widely identified as key barriers to uptake of mixed farming and other climate mitigation practices (Bell and Moore, 2012, Schut et al., 2021, Kragt et al., 2017, Wreford et al., 2017, Smith and Olesen, 2010). This can result in reliance on contractors to complete work which is also

costly and can be difficult to arrange for when conditions are suitable and the crop is ready, especially as contractors may not prioritise small jobs and their machinery can be too big for small fields and gateways.

"Price of gear… We'd have to get contractors to do everything, and then you're at their beck and call… I can see that, you know, there's some benefits to putting, you know, having a field of corn in, but I think it's cheaper not to." – Northumberland farmer 2

Economic trade-offs were also highlighted, with some farmers recognising the need to reduce the livestock kept on the farm if they used some fields to grow arable crops, and conversely an industry representative noted the reduction in total crop yields for arable farms that incorporated grass leys into their rotations (Table A5.4).

"I felt we were a bit overstocked last summer, I think, last year, when we had that dry period… I just felt that I wish I'd got a bit more grass. Probably haven't got the balance right still. I mean, you could argue, you know, reduce the stock numbers and keep the barley. But then I was able to buy barley last year for £145 a tonne at harvest… I just thought I could buy barley cheap. I wouldn't be able to say the same thing today barley's £200[3] a tonne." – Northumberland farmer 4

[3] Correct at time of interview in December 2021

Regarding sending stock away to temporary grassland or overwinter forage or cover crops, although no farmers interviewed did this, perceived benefits included: i) the ability to outwinter stock at low cost while resting their own fields, ii) reduced dependence on bought-in inputs for overwinter feed, iii) a potentially reduced winter workload, and iv) for some, a low-cost way to enter the industry or increase their stock. In terms of disadvantages, both industry representatives and farmers identified lack of infrastructure to fence, water and handle stock on arable farms, particularly cattle, and labour to look after stock (either unavailability of skilled labour on or near arable farms with stock, or labour burden of livestock farmer having to travel to arable farm to look stock) (Table A5.4). These disadvantages are well-characterised as barriers to integrating livestock into arable and similar climate friendly or carbon farming practices (Bell and Moore, 2012, Schut et al., 2021, Wreford et al., 2017). This is accentuated by the difficulty for arable and livestock farmers to identify respectively interested parties to form partnerships, and the spatial separation of arable and livestock farming areas in the UK making transport and husbandry of livestock challenging and expensive (Table A5.4).

7.5.2. Factors influencing adoption

7.5.2.1. Rational reasons for non-adoption

Vanclay and Lawrence (1994) identified eleven categories of rational reasons that farmers may have for not adopting seemingly beneficial management practices: complexity of intervention, inability to trial or partially adopt, incompatibility with farm and personal objectives, loss of flexibility, risk of failure, conflicting information

regarding benefits, cost of implementation, infrastructure requirements, and limited economic benefit. We consider each of these in turn and discuss the extent to which these may apply to the management practices studied here.

Capital outlay required for adoption was seen as an issue for rotational grazing in terms of fencing and water infrastructure required, herbal leys regarding the cost of reseeding, and ley-arable (mixed farming) in terms of the ability of livestock farms to afford arable equipment. However, the extent to which this constrained adoption depended on other aspects of the farms' circumstance. For example, farmers that had an existing small field structure (particularly relevant in Devon where maintaining or restoring hedges which created small fields had high cultural value) found it easier to adopt rotational grazing compared to farms with on average larger fields that would require substantial up-front investment to divide and provide water to. Furthermore, industry representatives noted that where farmers rented land on short-term leases this limited the viability of investing in infrastructure. Although electric fencing can provide a cheaper entry point for rotational grazing, this was not widely used by the adopting respondents here. Additionally, farmers that had diversified into contracting did not regard cost of equipment for mixed farming or reseeding as an issue due to already having the necessary machinery availability. The economics of adoption was mainly raised in relation to tree planting, due to perceptions that farming was a more profitable land use and the fact that planting trees overall costs farmers money even with grant support. Industry representatives also highlighted the long time before a return from timber harvesting, and uncertainty about future

government support payments or carbon markets, as factors that negatively influenced the economics of tree planting. Mixed farming (ley-arable) also has economic constraints in market conditions where cereal animal feeds are cheaper for farmers to buy in than grow on farm.

Regarding congruence or compatibility with farm objectives, this was most clearly expressed for trees on farms by farmers who identified strongly as food producers or were reluctant to plant trees ‘for the sake of it’, particularly where farms already had substantial tree and hedge cover. Conversely, where farmers felt their land lacked shelter or they had an interest in game shooting, the presence of trees or hedges on their farms helped them meet their objectives and was viewed positively. Rotational grazing and herbal leys were most likely to be incompatible with farm objectives where farmers had specialised systems. For example, one farmer provided supplementary cereal feed to finishing cattle during the grazing season so felt that moving feeders would be challenging in a rotational grazing system and did not prioritise grass productivity as highly because livestock performance was underpinned by the supplementary feed. Another bred pedigree cattle which required splitting the herd into small groups of varying sizes to run with different bulls for mating, which again made implementing a rotation system more challenging. Other farmers relied on high-performance perennial ryegrasses (*L. perenne*) for forage productivity and felt that including herb species that had received less plant breeding attention may struggle to compete in these swards. One industry representative identified that where farmers have exclusively permanent pasture, they are not

conducting any reseeding so are unlikely to consider a herbal ley. Furthermore, industry representatives identified that some farmers are not adopting RG or HL as they are coming towards the end of their careers and so are scaling back their farming activities and reducing their workload. This is often correlated with a shift to relying on environmental schemes for income rather than farm productivity, so such farmers are not interested in management practices that increase workload for productivity gains that they don't want or need. This position may become less financially sustainable as the Basic Payment Scheme is withdrawn in England and replaced with Environmental Land Management schemes with anticipated lower net payments to be received by farms. Regarding adopting mixed farming (ley-arable), non-adopting farmers highlighted a trade-off with stock carrying capacity if they used some land to grow crops, implying this was counter to their objectives.

The risk or uncertainty that a practice would deliver desired outcomes was seen as a particular issue for herbal leys. Some farmers cited concerns that the yield or productivity was unknown for them or could be less than conventional leys, and some herb species were seen to be unsuitable to a given farmer's climate or soil type. Relatedly, industry representatives noted that herbal leys can be difficult to establish, and more broadly that reseeding pasture comes with a risk of failure particularly if there is a high weed burden or drought conditions impair germination. This relates to conflicting information about the applicability or effectiveness of a practice; some farmers and industry representatives felt that any benefits of herbal leys could be equally achieved through well-managed grass and clover leys, and

questioned whether herbal leys do in fact have anthelmintic properties. Regarding rotational grazing, there was also uncertainty about whether this would in fact improve forage or livestock growth, with one industry representative noting the potential for reduced livestock performance if rotational grazing wasn't managed correctly, and indeed acknowledgment in the literature that the perceived benefits of rotational grazing are not realised universally (Briske et al., 2011, Gillespie et al., 2008).

Loss of flexibility was perceived as a particular issue for herbal leys and trees on farms. Herbal leys need to be grazed rotationally and the stock removed in the winter to ensure persistence of more sensitive herb species, and there are ongoing concerns about ewe fertility on swards with a high red clover content. Regarding trees on farms, some farmers highlighted the inconvenience of in-field trees to their farming operations, and the loss of flexibility due to the permanence of land use change following tree planting via compulsory re-stocking requirements following felling. On the other hand, trees on farms are highly 'divisible' or trial-able (i.e. able to be partially adopted). This may partially account for the high level of uptake of this practice among respondents, as farmers have a high degree of control over the manner and scale of integrating trees onto their farms. In contrast, mixed farming (ley-arable) has low divisibility due to the economics of scale required to justify capital outlay in equipment.

Industry representatives identified farmer confidence as a factor limiting adoption of rotational grazing and herbal leys, corresponding with intellectual outlay (the requirement to learn new ways of doing things). Some farmers similarly identified they would need to seek advice from professionals or existing adopters before implementing these practices, and one farmer citing a lack of time and energy as part of the reason they had not tried growing herbal leys. However, the related issue of complexity was not raised for any of the management practices investigated here by farmers or industry representatives, i.e. although non-adopting farmers may need additional knowledge to implement these successfully, any potential increase in complexity is not deterring them. Physical and social infrastructure only appeared to be an issue for ley-arable systems, in particular relating to sending stock to arable, due to i) the lack of infrastructure for livestock on arable farms (fencing, water, handling), ii) the widespread spatial separation of livestock and arable farming areas in England resulting in limited livestock availability close to arable farms, and iii) the difficulty of livestock and arable farmers identifying interested parties to form a partnership.

Although not included by Vanclay and Lawrence (1994) in their framework, farm geography (particularly climate and soil type) may be a further rational basis for why farmers do or don’t adopt certain management practices. For example, one farmer viewed rotational grazing as unworkable on their farm due to concerns about soil damage from poaching in wet weather, exacerbated by that farm’s poorly draining soils and high spring and autumn rainfall. Similarly, farmers in Devon (typically high

rainfall including during the growing season) did not value the deep-rooted properties of herbal leys in delivering drought tolerance, whereas another respondent on shallow and free draining soils viewed deep rooting herbal leys as essential in ensuring sustained forage productivity on their farm. These inherent sources of variability between farms are potentially important in understanding differences in attitudes to adoption of certain management practices

7.5.2.2. Types of farmer

In our analysis of farmer interviews, four groups of farmers became apparent, based on their revealed priorities and reasons for adopting practices considered here or not. Firstly, some farmers appeared to be aware of and in agreement with the principles of Regenerative Agriculture (Newton et al., 2020, Schreefel et al., 2020, Moyer et al., 2020), and framed their farming decisions in this holistic context. These farmers had an ideological motive that adopting regenerative practices (RG, HL and trees on farms) is how farming should be done and the way livestock should be kept. This grouping would fall within the ‘enthusiast/hobbyist’ segment identified by Rehman et al. (2008) or Group B of Defra (2011), particularly in that farming was not the main source of income.

A second group could be described as Regenerative Agriculture practice pragmatists, in that they readily engaged with practices such as RG and HL without buying into the more holistic regenerative principles underlying these and would not see themselves as ‘regenerative’ farmers (Gosnell et al., 2019). Instead, practices

were adopted because they were perceived as the latest innovations to increase productivity, and as a means to future-proof the business to future subsidy changes. This could relate to the 'family orientation' segment identified by Rehman et al. (2008) and Groups A or C of Defra (2011). This group also matches the perceptions of industry representatives that adopters of RG and HL tend to be younger and focused on maximising productivity, and potentially more progressive, open-minded, willing to try new things or 'forward thinking' in their outlook.

A third group were more explicitly business-focused, in that their priority in considering adopting practices was how much it could increase farm income, particularly relating to eligibility for farm support payments, and were reasonably clear-eyed in recognising that land management decisions needed to be profitable and deliver an income from the farm. This corresponds with the 'business/entrepreneur' segment of Rehman et al. (2008) and Group C of Defra (2011). This was notably relevant to reasons for tree planting and accords with perceptions of industry representatives that owner occupiers are particularly likely to consider tree planting as a form of income diversification.

Finally, some farmers strongly identified as food producers. These farmers operated relatively intensive (use of inorganic fertilisers and cereal-based animal feeds) and largely conventional systems (e.g. didn't adopt RG or HL), and were wary of changes in management practice that would shift their enterprise focus from food production. These farmers expressed a strong desire to earn a livelihood from producing food

without having to rely on government support payments. This could relate to the 'independent/small farmer' segment of Rehman et al. (2008) (although the farmers in question here were not small-scale producers) or Group D of Defra (2011). Industry representatives described non-adopters of RG and HL as typically more traditional or resistant to change, which may be correct in some instances but farmers in this group ran modern, productive systems and had rational reasons for not adopting these practices (Section 3.2.1).

7.5.3. Implications for policy

Knowledge exchange was seen as particularly important in facilitating adoption of rotational grazing and herbal leys by industry representative and farmers who had adopted each practice, and this could help address the constraints of risk or uncertainty, conflicting information and intellectual outlay (Section 3.2.1). Industry representatives referred to the benefits of case study farms and field trials, suggesting that demonstrating how to implement these in practice and the potential for productivity gains in particular could help convince non-adopting farmers. Farmers interviewed had a slightly different emphasis, highlighting the importance of talking to an existing adopter they know or trusted source of advice for pointers, advice and to learn from their mistakes. Regarding productivity, one farmer suggested they would appreciate the means to see the productivity benefits on their own farm (e.g. infrastructure to monitor livestock growth rates) rather than having to rely on industry-wide examples or case studies from 'model' farms. Another farmer wanted to gain experience from existing adopters but expressed frustration that they

rarely have time to attend formal knowledge exchange events such as monitor farm open days. This suggests potential limitations of the ‘top-down’ knowledge exchange model in reaching non-adopting farmers, corresponding with the findings of Rose et al. (2018a) that farmers’ informal networks and existing trusted sources of advice are currently under-utilised opportunities for knowledge exchange.

Perceptions of the role of government financial support differed between interventions. For rotational grazing, herbal leys and sending stock to arable farms, industry representatives and farmers widely suggested that capital grants to help with infrastructure costs (rotational grazing and ley-arable) or reseeding equipment (e.g. direct drills for herbal leys) would further increase uptake, rather than payments for adoption per se. This accords with the increasingly widespread acknowledgement that farmers are not simply motivated by profit maximisation (Journeaux et al., 2018), but rather this form of incentive helps overcome the capital outlay constraint discussed in Section 3.2.1. Regarding sending stock to arable farms (ley-arable), respondents noted the risk of disparity if support payments are directed at arable farmers to encourage improved soil health without necessarily rewarding the livestock farmer who has provided the stock, which could be mitigated through careful scheme design. Farmers widely reported a net financial cost from planting trees even with government support payments, and it was suggested by both industry representatives and farmers that were this economic constraint (Section 3.2.1) overcome by increasing payment rates, in addition to sufficiently long-term maintenance payments, then farmers would readily plant more trees. Indeed, it is

difficult to see how the UK government's tree planting targets will be met in England based on current levels of grant uptake (Jordon and Wentworth, 2021). Again, crucially, this is not to assert that farmers are exclusively motivated by money, but rather to acknowledge that farmers cannot be expected to perform actions that deliver mostly public benefits at a net private cost to themselves (Vanclay and Lawrence, 1994).

7.6. Conclusion

We provide an initial indication of the advantages and disadvantages of four management practices (rotational grazing, herbal leys, trees on farms and ley-arable rotations) from the perspective of selected English sheep and beef cattle livestock farmers. These have previously been demonstrated to increase farm productivity and/or carbon stocks and are already incentivised through various mechanisms by Defra in England (Table 7.1). However, we identify disadvantages to adopting these practices, which in turn contribute to rational reasons for farmers not to adopt. In addition, some farmers are more receptive than others to such practices based on their outlook and values. Given further adoption of these practices is likely required to meet the UK's climate change mitigation targets, we suggest how support available to farmers (knowledge exchange and incentives) could be modified to promote uptake. Our findings also provide the basis for future work with a more rigorous theoretical underpinning, e.g. using the Theory of Planned Behaviour, to understand the likely extent of further adoption of these practices.

It is important to recognise that complete uptake of some practices may not be i) desirable, as they are not universally beneficial, or ii) achievable, as some reasons for non-adoption such as farm geography or farmer objectives are not necessarily addressable through extension activities or incentives. Policymakers need to further recognise the rational reasons farmers have for not adopting seemingly beneficial interventions, in order to establish whether targets for increased uptake of certain management practices (e.g. tree planting) are achievable with the current incentive structures. This will be key in designing land management scenarios that not only address major challenges like climate change mitigation in theory (Climate Change Committee, 2020) but are also achievable in practice.

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Chapter 8. Conclusion

8.1. Main findings

In my thesis, I consider a suite of alternative land management practices in temperate regions that have been proposed to deliver one or a combination of increased farmland carbon stocks and enhanced agricultural productivity (including crop yield, pasture dry matter production and livestock growth rates). These practices are all already adopted to some extent and have been sufficiently studied in temperate oceanic regions to facilitate evidence syntheses.

My key findings are as follows:

1. **Reducing tillage intensity and integrating a grass-based ley phase into crop rotations can increase soil organic carbon (SOC) concentration without negatively impacting crop yield**

Reduced tillage likely increases SOC through enhanced soil aggregation and lower soil temperatures which both decrease the rate of decay (Huang et al., 2018). Ley-arable systems also improve aggregate stability from reduced cultivation frequency, but mainly boost SOC through increased plant residue inputs in the grass phase from enhanced rooting structure and depth compared to annual crops (Soussana et al., 2004, Conant et al., 2001). In addition, I found no negative effect on crop yield, but this may be due to the moderating effect of inorganic fertilisers which I was

unable to account for in the meta-analysis. Another Regenerative Agriculture (RA) technique, namely over-winter cover cropping, had no demonstrable effect on SOC or arable crop yield, which could in part be due to the limited post-harvest growing season for cover crops in the cooler and higher latitude regions covered by my systematic review and again the moderating impact of inorganic fertilisers (Poeplau and Don, 2015, Abdalla et al., 2019, Jian et al., 2020).

In all, demonstrating increases in SOC concentration without a yield penalty for reduced tillage intensity and ley-arable rotations is likely to increase the appeal of adopting these two practices to land managers (Burton, 2004, Wynne-Jones, 2013). However, I did not find evidence to support the claim made by some proponents that RA can deliver a SOC-yield win-win in these temperate oceanic regions.

2. **Transitioning from continuous to rotational grazing, incorporating perennial forbs into pasture swards to form multi-species or herbal leys and integrating trees onto farms via agroforestry systems increases pasture productivity and sheep and cattle growth rates.**

This increase in productivity in rotational grazing systems is likely related to the beneficial impact of rest (time ungrazed which allows the plant to recover) on forage leaf and root development enabling rapid regrowth following a short grazing event (Sanderman et al., 2015, Hacker, 1993, Voisin, 1959, Savory and Butterfield, 2016). Regarding herbal leys, I was able to corroborate theoretical mechanistic

expectations of herbage dry matter production being increased by i) legume incorporation, ii) enhanced sward rooting depth and iii) increased plant species diversity, and livestock growth rates being boosted by higher leaf protein contents (Cranston et al., 2015, Luscher et al., 2014, Weisser et al., 2017). I was unable to analyse the impacts of rotational grazing and herbal lays on SOC due to a lack of evidence (Conant et al., 2017), although plausible mechanisms exist for these interventions to increase inputs of plant residues to the soil which warrant further empirical investigation.

Finally, my narrative synthesis of temperate agroforestry provided a first overview across multiple environmental, economic and productivity outcomes. I identified an emerging evidence base that demonstrates that integrating trees onto temperate livestock (sheep and cattle) farms through agroforestry practices can deliver a suite of environmental benefits (carbon sequestration, improved water quality, flood hazard mitigation and reduced soil erosion) alongside positively impacting enterprise economics (Torralba et al., 2016, Mayer et al., 2022, Kay et al., 2017, Kay et al., 2019, Cole et al., 2020). Although increased tree integration tends to negatively impact pasture productivity, livestock growth rates can often benefit, and heat and cold stress are reduced. For example, it has been established by recent meta-analyses with similar geographic extent that adopting agroforestry systems has the effect of enhancing soil carbon stocks and increasing overall productivity (tree plus understory component) (Mayer et al., 2022, Pent, 2020, Chatterjee et al., 2018).

In order to determine the potential for RA practices to contribute to climate change mitigation efforts through soil carbon sequestration, I used the data assembled in Chapter 3 to simulate the potential change in SOC stocks from complete uptake of these practices across arable land Great Britain (GB).

3. **Soil carbon sequestration from adopting cover crops could mitigate 16% of current GB agricultural emissions over 30 years, whereas a rotation of four years ley – two years arable cropping could mitigate 27%.**

While this finding is based on simplifying assumptions of no prior adoption and that complete adoption would be possible, it does indicate a non-trivial role for these practices in regional climate change mitigation efforts. Compared with previous work, these practices would only sequester around 10% of the emissions abatement possible from afforesting land made available via agricultural productivity gains (Lamb et al., 2016). However, RA practices have the added advantage of enabling continued food production. Not only will this likely have greater appeal to farmers, it also has the potential to reduce the risk of displacing food production and associated environmental harms overseas (Fujimori et al., 2022, de Ruiter et al., 2016).

4. **Reasons for non-adoption of RA management practices by English livestock farmers including prohibitive capital outlay required, incompatibility with their farming objectives, and the risk that a practice would not deliver the desired benefits.**

Although the RA practices synthesised in my DPhil have demonstrable benefits for soil carbon sequestration and/or agricultural productivity – and are all incentivised and adopted to some extent in the UK (see Table 7.1 and citations therein) – large portions of the farming community are not adopting these practices (Rose et al., 2018, Vanclay and Lawrence, 1994). Understanding the reasons behind this is key to determining whether the theoretical benefits demonstrated above are achievable in practice, therefore determining the utility of these practices in national climate change mitigation efforts, amongst other things. From my semi-structured interviews, I found that although farmers widely recognise the potential of RA practices in terms of increased productivity, shelter and shade, they were less interested in their potential for carbon sequestration or reducing greenhouse gas emissions. Furthermore, farmers identified practical considerations and limitations to adopting RA management practices which are frequently overlooked by policy makers seeking to promote their uptake for climate change mitigation or delivery of other environmental benefits. Promoting peer-to-peer rather than top-down knowledge exchange and targeting financial incentives to help meet capital outlay costs would both likely help further increase adoption of these practices.

8.2. Additional findings and limitations

i) Some RA practices can contribute to improving the sustainability of ruminant livestock production

Some of the RA practices I considered in my thesis are also relevant to the discussion around improving environmental sustainability of ruminant livestock production. Of most apparent benefit, I demonstrate that both rotational grazing and herbal leys improve livestock growth rates (Chapter 6), which contributes to reducing lifetime emissions per animal (Herrero et al., 2016). Further, forage with higher leaf protein content (promoted by inclusion of leguminous herbs into the sward) is more digestible, again lowering methane production. However, care must be taken when boosting dietary crude protein intake as this is susceptible to breakdown in the rumen thus increasing ruminant-associated emissions of nitrous oxide (Cranston et al., 2015, Luscher et al., 2014). Herbal leys containing species with high leaf condensed tannin concentrations (e.g. chicory, *Cichorium intybus*; Birdsfoot trefoil, *Lotus corniculatus*; or Sulla, *Hedysarum coronarium*) may reduce internal parasite burdens (Luscher et al., 2014). Although I was unable to corroborate this from meta-analysis of evidence available from temperate oceanic regions, a reduced parasite burden would in turn reduce methane emissions per unit of dry matter intake (Fox et al., 2018). In addition, condensed tannins potentially directly inhibiting methanogenic bacteria in the rumen (Luscher et al., 2014).

Beyond options for reducing livestock emissions, there is some interest in directly ‘offsetting’ livestock emissions through compensatory carbon sequestration on farms. Although the ability to further increase soil carbon stocks in well-managed grasslands can be limited (Smith, 2014, Conant et al., 2017), integrating trees onto

farms through agroforestry provides a widely applicable option to increase terrestrial carbon stocks for livestock emissions abatement (Doran-Browne et al., 2018, Doran-Browne et al., 2016, Briner et al., 2011, Petersen et al., 2003, Dube et al., 2011, Ripamonti and den Herder, 2019). However, this mitigation strategy may not be appropriate for large scale application due to:

i. the carbon stocks in both soils and tree biomass eventually saturating;
ii. the risk of non-permanence following discontinuation of beneficial management (e.g. trees felled and not restocked);
iii. the potential for displacement of carbon stocks through - for example - compensatory deforestation to create farmland elsewhere; and
iv. difficulties in verifying sequestration (Smith, 2012, Lorenz and Lal, 2014).

Furthermore, offsetting methane (CH_4) emissions via carbon dioxide (CO_2) sequestration is of questionable merit due to these two GHGs having different atmospheric dynamics. CO_2 accumulates in the atmosphere and further warming is linearly correlated with emissions, whereas CH_4 – despite being a more potent GHG molecule for molecule than CO_2 – breaks down in the atmosphere after approximately 12 years, so stable levels of ongoing emissions do not cause additional warming (Allen et al., 2018). This leads some to suggest that livestock numbers do not need to be reduced to cease their contribution to *further* warming, although others argue that this short atmospheric lifespan makes methane a particularly attractive target for emissions reduction as this would decrease atmospheric methane concentrations, equivalent in atmospheric warming terms to

achieving carbon sequestration (Smith and Balmford, 2020, Lynch et al., 2021, Lynch and Garnett, 2021).

Finally, my thesis considers one management practice where livestock have potential to increase the sustainability of another farming system; integrating livestock into arable cropping through ley-arable rotations, as introduced in Chapter 1. Ley-arable systems are possible without integrating livestock; farmers in close proximity to anaerobic digestion facilities can repeatedly cut grass leys to input as feedstock for digestors in return for nutrient-rich digestate, and vegan growers use the ley-phase of rotations as a green manure e.g. (Tolhurst). Nevertheless, there is evidence of greater SOC gains from ley-arable systems that integrate livestock compared to stockless systems (Hanley and Ridgman, 1979, Schulz et al., 2017) and livestock can recycle nutrients fixed by plants into a form more readily available to the subsequent crop (Poffenbarger, 2010, Watson et al., 2000). Despite these benefits, the soil carbon increases possible from integrating livestock on temporary leys into arable rotations would not come close to offsetting livestock methane emissions from enteric fermentation, notwithstanding the issues with attempting to 'offset' livestock methane emissions with carbon sequestration as discussed above. Nevertheless, if grazing livestock were to be re-distributed on a national or regional scale from non-cropped areas on more marginal farmland in the uplands to arable regions, either seasonally (e.g. to graze overwinter cover or brassica crops) or permanently (e.g. onto multi-year leys rotated around an arable farm), this would potentially release areas of some upland or marginal farms for nature restoration or

afforestation as part of biodiversity loss or climate change mitigation strategies (Lamb et al., 2016, Climate Change Committee, 2020). This would be particularly beneficial if it coincided with a reduction in the area of cropland used to grow arable feeds for livestock (including cereals, oilseeds, pulses). Quantifying scenarios of the full GHGE implications (including potential increases in terrestrial carbon stocks) from such a national or regional transition is an important remaining knowledge gap.

ii) Findings from analysis of practices adopted as part of Regenerative Agriculture are not directly generalisable to holistic Regenerative Agriculture systems

Although I have covered the key principles of RA through the practices considered in my thesis (Table 1.1), there are reasons to expect that the findings of my thesis from individual practices now promoted as part of RA are not directly applicable to RA systems.

1. RA practitioners often adopt a greater intensity of management practices compared to that implemented as experimental treatments in published studies. For example, RA practitioners may implement mob grazing with high stocking densities, small paddock areas and long rest periods, compared to less intensive versions of rotational grazing, or grow cover crops or herbal leys containing ten or more different species compared to the monocultures or more simple mixes used in studies, as indicated in Fig 6.1.

2. Experimental studies typically implement prescriptive treatments, which although important for study replicability, contrasts with an often more holistic approach to decision making and adaptive management used by RA practitioners (Savory and Butterfield, 2016, Brown, 2018). This means that findings of experimental studies are often rejected by practitioners on the basis that they do not adequately represent the management strategies they utilise (Briske et al., 2011).

3. The studies that I synthesise in my thesis are typically implemented under a largely conventional agriculture approach, such that although a management practice may align with one principle of RA, the other principles are not followed. For example, diverse herbal leys or cover crops can be established using soil cultivation, herbicide applications and inorganic fertilisers, which would be contrary to a RA approach.

4. Relatedly, experimental studies typically implement only one management practice in isolation (although in Chapter 3 some studies did consider factorial implementation of reduced tillage, cover cropping, and incorporation of a ley phase), whereas RA practitioners implement multiple management practices simultaneously, including options not considered here such as pasture cropping, intercropping, alley cropping (Millar and Badgery, 2009, Ivezić et al., 2022, Ivezić et al., 2021, Mahmoud et al., 2022, Badgery et al., 2014) and

incorporating pastured pigs and poultry in addition to grazing ruminants (Brown, 2018).

These differences between holistic RA systems and the individual management practices widely implemented in experimental studies that I synthesise in my DPhil, lead to reasons to anticipate that my approach under- rather than over-predicts benefits.

Firstly, as discussed above, I consider management practices singly rather than in combination, whereas greater benefits would be expected from combined interventions (e.g. increasing plant residue inputs to arable soils through ley-arable rotations and cover crops, while simultaneously avoiding loss of soil aggregation and therefore SOC decay by reducing tillage intensity). However, the effect of implementing multiple practices would very probably be saturating rather than purely additive, with an equilibrium soil carbon stock still reached, albeit perhaps at a higher point, rather than continued sequestration (Smith, 2014, Powlson et al., 2011).

Secondly, in a conventional system where only one principle of soil health may be met (Table 1.1), it is hard to achieve conditions where key mechanisms promoted by RA practitioners take effect. For example, enhancing soil biology via implementing all principles of soil health simultaneously may result in increased plant-available nutrients which would benefit crop yield (Moyer et al., 2020).

Nevertheless, in all, my thesis provides an important first step to test proposed benefits of RA through understanding the underlying mechanisms using existing empirical data. Future research should investigate such holistic systems through observational experiments with pre-implementation baseline data collection, that compare a) conventional systems, b) RA practices implemented in prescriptive experimental systems using a factorial design, and c) holistically or adaptively managed RA systems. While it would be hard to replicate holistic or adaptive management in an experimental context, an observational approach with sufficient replication and adequate baselining would substantially address this knowledge gap. This could be coupled with detailed experimental manipulations to test mechanisms for increased carbon sequestration or productivity following implementation of RA practices, such as manipulations or measurements of rooting depths in different species as part herbal leys, or improved understanding of the relationship between above- and below-ground dynamics of forage plants in rotational grazing systems. Finally, my thesis presents results generalisable to temperate oceanic regions which is useful for informing future research and policy but is of little use for application in specific farming contexts. A greater understanding of the mechanisms driving these results would give land managers greater confidence in the likelihood of achieving desired outcomes from implementing a given practice.

8.3. Should Regenerative Agriculture practices be further promoted in the UK?

In summary, my thesis confirms that ley-arable systems and reduced tillage intensity increase soil organic carbon (SOC) concentration in temperate oceanic regions compared to continuous arable cropping with full-inversion tillage. Cover cropping and ley-arable systems are most advantageous in increasing SOC stocks, although the carbon sequestration achievable would likely only partially offset existing agricultural emissions with limited potential for Scope 3 offsetting (Elliott et al., 2022). This occurs without any yield penalty in cropping years, but there is a risk of displaced cultivation from adopting ley-arable systems without a corresponding restructuring in livestock feeding regimes to free up farmland from growing animals feed crops (Karlsson and Röös, 2019). Rotational grazing and herbal leys offer clear productivity benefits both in terms of increased forage production and improved livestock growth rates, although there is currently a lack of evidence to determine their impact on SOC stocks. Inclusion of trees into livestock farming systems through well-designed agroforestry systems increases carbon stocks compared to the equivalent number of trees being separate from pasture as woodland (Fornara et al., 2017, Beckert et al., 2015, Upson et al., 2016). However, trees can have a variable impact on pasture production, livestock growth rates and heat and cold stress, depending on system design and local climate.

RA practices also offer routes to reducing emissions associated with ruminant livestock production, largely through productivity improvements. In addition, there are

other benefits from having sheep and cattle in a regional food system (i.e. in ley-arable systems). However, RA is clearly not a panacea for achieving net zero emissions ruminant livestock production.

Therefore, although sufficient studies of holistic regenerative systems are yet to emerge to enable quantitative synthesis, I argue that sufficient evidence exists to promote further uptake of the management practices considered here. Furthermore, achievable adjustments to current knowledge exchange programmes and financial incentives could be made to stimulate increased uptake by farmers. It remains to be seen whether land managers need to buy into the holistic and adaptive RA paradigm in order to deliver desired benefits, or whether similar results can be achieved through careful implementation in an otherwise conventional system by implementing a suite of beneficial management practices.

8.4. References

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Appendix 1. Supplementary Materials for Chapter 2

A1.1. Search strategy

A1.1.1. Search string

sheep OR ewe* OR lamb OR lambs OR lambing OR "Ovis aries" OR ovine OR “Bos taurus” beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR calving OR bovine OR grazed OR grazing OR graze OR ruminant OR ruminants OR livestock OR pasture OR pastures OR pastoral

AND

tree OR trees OR shrub OR shrubs OR shrubby OR wood OR woodland OR woods OR woodlot* OR forest OR forests OR forestry OR silvopast* OR sylvopast* OR silvipast* OR sylvipast* OR agriforest* OR agroforest* OR silvo-past* OR sylvo-past* OR silvi-past* OR sylvi-past* OR agri-forest* OR agro-forest* OR agrosilvopast* OR agrisilvopast* OR agrosylvopast* OR agrisylvopast* OR agrosilvipast* OR agrisilvipast* OR agrosylvipast* OR agrisylvipast* OR "wood past*" OR dehesa OR dehesas OR montado OR montados OR bocage OR bocages OR shelterbelt OR shelterbelts OR “wind break*” OR windbreak* OR “riparian buffer*” OR “riparian strip*” OR “buffer strip” OR hedge OR hedges OR hedging OR orchard OR orchards OR "multipurpose tree*" OR intercrop* OR “alley crop*” OR “row system” OR “row systems” OR “clump system” OR “clump systems” OR “linear feature” OR “linear features” OR biofuel OR biofuels OR bioenergy OR coppic* OR “short rotation woody crop*” OR “short-rotation forest*” OR fuelwood OR “fuel wood”

AND

“environment* benefit*” OR “environment* impact*” OR externality OR externalities OR "greenhouse gas*" OR GHG OR GHGE OR GHGs OR GHGEs OR offset* OR mitigat* OR sequest* OR emission* OR abate OR abates OR abating OR abatement OR carbon OR "air pollut*" OR methane OR "nitr* oxide" OR "nitr* oxides" OR "nitr* dioxide" OR "nitr* dioxides" OR "climate chang*" OR "global warm*" OR flood* OR “water flow regulat*” OR hydrolog* OR infiltrat* OR “water quality” OR “water puri*” OR “dissolved solids” OR “suspended solids” OR sediment* OR nutrient* OR “run off” OR runoff OR fertilis* OR fertiliz* OR manur* OR pollut* OR nitrogen OR nitrate OR phosphorous OR phosphorus OR phosphate OR “air qualit*” OR ammonia OR ammonium OR odo*r OR erosion OR erode OR eroding OR eroded OR erodes OR “soil loss*” OR “soil degrad*” OR productivity OR production OR “animal health” OR “animal welfare” OR “shade” OR shelter OR “heat stress” OR “cold stress” OR “tree-animal synerg*” OR “cattle cool*” OR “sheep cool*” OR “animal perform*” OR liveweight OR bioclimat* OR “growth rate” OR pasture OR pastures OR “wind protect*” OR microclimate* OR yield OR “carrying capacity” OR financ* OR economic* OR “bio-economic model*” OR “cost-benefit analysis” OR diversif*

AND

Temperate OR “UK” OR “United Kingdom” OR England OR Scotland OR Wales OR “Northern Ireland” OR English OR Welsh OR Scottish OR Irish OR Europ* OR Germany OR France OR Italy OR Spain OR Ukraine OR Poland OR Romania OR Netherlands OR Holland OR Belgium OR Czech* OR Greece OR Portugal OR Sweden OR Hungary OR Belarus OR Austria OR Serbia OR Switzerland OR

Bulgaria OR Denmark OR Finland OR Slovakia OR Norway OR Ireland OR Croatia OR Moldova OR Bosnia OR Albania OR Macedonia OR Slovenia OR Latvia OR Estonia OR Montenegro OR Luxembourg OR Malta OR Iceland OR Andorra OR Monaco OR Liechtenstein OR "San Marino" OR "Channel Islands" OR "Isle of Man" OR Gibraltar OR "Faroe Islands" OR Yugoslavia OR German OR French OR Italian OR Spanish OR Ukrainian OR Polish OR Romanian OR Dutch OR Belgian OR Czech* OR Greek OR Portuguese OR Swedish OR Hungarian OR Belarusian OR Austrian OR Serbian OR Swiss OR Bulgarian OR Danish OR Finnish OR Slovakian OR Norwegian OR Croatian OR Moldavian OR Bosnian OR Albanian OR Macedonian OR Slovenian OR Latvian OR Estonian OR Montenegrin OR Luxembourgish OR Maltese OR Icelandic OR Andorran OR Monegasque OR Sammarinese OR Manx OR Yugoslav OR Canada OR "USA" OR "North America" OR "United States of America" OR "US" OR Canadian OR American OR Chile OR Patagonia OR Argentina OR Chilean OR Patagonian OR Argentinean OR Australi* OR "New Zealand"

A1.1.1.1. Further details

An identical search string was used to search Web of Science, Scopus and CAB Abstracts on 2 October 2019, with the exceptions of the removal of the "US" term in CAB Abstracts and the addition of "TITLE-ABS-KEY" syntax required by Scopus. Web of Science was searched across 'All Databases' which included:

- Web of Science Core Collection (1900-present)
  - Science Citation Index Expanded (1900-present)

- Social Sciences Citation Index (1900-present)
- Arts & Humanities Citation Index (1975-present)
- Conference Proceedings Citation Index- Science (1990-present)
- Conference Proceedings Citation Index- Social Science & Humanities (1990-present)
- Book Citation Index– Science (2005-present)
- Book Citation Index– Social Sciences & Humanities (2005-present)
- Emerging Sources Citation Index (2015-present)
- Current Chemical Reactions (1986-present)

(Includes Institut National de la Propriete Industrielle structure data back to 1840)

- Index Chemicus (1993-present)

- BIOSIS Citation Index (1969-present)
- Current Contents Connect (1998-present)
- Data Citation Index (1993-present)
- Derwent Innovations Index (1993-present)
- KCI-Korean Journal Database (1980-present)
- MEDLINE® (1950-present)
- Russian Science Citation Index (2005-present)
- SciELO Citation Index (2002-present)
- Zoological Record (1993-present)

A1.1.2. Stakeholder engagement

Emails were sent on 2 October 2019 to the following temperate agroforestry organisations, using contacts available in Gordon et al. (2018):

- Farm Woodland Forum - UK - JISC maillist
- European Agroforestry Federation (EURAF) - euraf@agroforestry.eu
- Australian Agroforestry Foundation - admin@agroforestry.org.au
- Association for Temperature Agroforestry - North America - online form submission
- Poplar and Willow Research Trust - New Zealand - ian.mcivor@plantandfood.co.nz

The following email was circulated:

Dear concerned,

I am a PhD student at the University of Oxford, United Kingdom, researching the potential for agroforestry to increase the sustainability of sheep and cattle (beef and dairy) production. I am contacting your organisation for feedback on a systematic literature review proposal.

I am in the process of systematically mapping the evidence base to answer the question: "What are the impacts of temperate silvopastoral systems on sheep and cattle productivity, environmental impacts* and farm economic viability?"

* specifically focusing on greenhouse gas emissions, reduced water and air quality, increased flood hazard and enhanced soil erosion attributed to sheep and cattle farming. I am interested in how agroforestry could mitigate some/all of these.

I am following the Collaboration for Environmental Evidence guidelines, and so am contacting relevant stakeholders to:

1) receive feedback on the applicability and necessity of this work;

2) determine how best to improve and hone the review question to ensure the findings are most relevant and useful to practitioners; and

3) request submissions of any studies that you are aware of that are particularly relevant to this question, particularly grey literature that might not be findable using online bibliographic database searches.

I would be very grateful if you could circulate this to your members, with a request for feedback on the review question and/or links to relevant studies, emailed to mattthew.jordon@zoo.ox.ac.uk

Very best wishes,

Matt Jordon

Replies to this email (exclusively from the UK Farm Woodland Forum and EURAF) provided 14 articles that we could access but weren't already present in our search results. These were incorporated into the grey literature screening process.

A1.1.3. Organisation websites searched for grey literature

Organisation websites were searched over the week beginning 16 March 2020. The websites searched, and number of relevant articles downloaded from each after title screening, is given in Table A1.1. In total, combined with the articles received through the stakeholder engagement emails (Appendix A.2), this resulted in 132

articles taken to grey literature abstract screening (Fig 2.1). Relevant grey literature records that were already present in the ‘records after abstract screening’ (from the bibliographic databases searched) were not counted or included again.

Table A1.1. Organisational websites searched for grey literature

Country/ Region	Organisation	Website address	Number of articles retrieved
UK	Woodland Trust	https://www.woodlandtrust.org.uk/	15
	Forest Research	https://www.forestresearch.gov.uk/	15
	Organic Research Centre	http://www.organicresearchcentre.com/	4
	ClimateXChange	https://www.climatexchange.org.uk/	3
	Farm Woodland Forum	https://www.agroforestry.ac.uk/	0
	Game and Wildlife Conservation Trust	https://www.gwct.org.uk/	0
	Agricology†	https://www.agricology.co.uk/	0
	Soil Association†	https://www.soilassociation.org/	0
Europe	European Agroforestry Federation (EURAF)	https://euraf.isa.utl.pt/welcome	11
	Agroforestry Innovation Networks (AFINET)	http://www.eurafagroforestry.eu/afinet	35
	AGroFORestry that Will Advance Rural Development (AGFORWARD)	https://www.agforward.eu/index.php/en/	12
	European Forestry Institute (EFI)	https://www.efi.int/	0
New Zealand	The New Zealand Poplar and Willow Research Trust	https://www.poplarandwillow.org.nz/	23
Australia	Australian Agroforestry Foundation	http://agroforestry.org.au/	0
USA	Association for Temperate Agroforestry	https://www.aftaweb.org/	0

†Agricology and the Soil Association contained relevant articles, but these had already been found through the Woodland Trust website

A1.1.4. Test list used to estimate comprehensiveness of search

Productivity - (Hawke, 1991, Hawke et al., 1993, Hawke and Wedderburn, 1994, Guevara-Escobar et al., 1997, Bird, 1998, Douglas et al., 2001, Teklehaimanot et al., 2002, Benavides et al., 2009)

Environmental impacts

- GHGEs – (Briner et al., 2012, Lorenz and Lal, 2014, Beckert et al., 2016, Doran-Browne et al., 2016)
- Flood hazard – (Carroll et al., 2004, Marshall et al., 2014, Lunka and Patil, 2016)
- Water quality – (Udawatta et al., 2010, Wang et al., 2012)
- Air quality – (Lin et al., 2006, Bealey et al., 2014)
- Soil erosion – (Mead, 1995, McIvor et al., 2008)

Economics - (Doyle et al., 1986, Sibbald, 2006)

A1.1.4.1. Notes on final inclusion of test list articles

All of the above articles were found using the search terms given in Appendix A.1. Bealey et al. (2014), Benavides et al. (2009), Bird (1998), Lorenz and Lal (2014) and Mead (1995) were excluded at the full-text screening stage under 'Review' because they did not contain any primary data. Hawke et al. (1994) and Lin et al. (2006) were excluded at the full-text stage under 'Outcome', and McIvor et al. (2008) excluded at the abstract screening stage, due to not meeting the inclusion criteria (Appendix B.2). All other studies were screened as relevant at the full-text stage and coded accordingly.

A1.2. Article screening

MWJ conducted all title and abstract screening. WJH and LP searched for all article full texts, apart from grey literature which was searched for and screened by MWJ. MWJ and WJH shared full text screening and data coding. Articles that met all the

PICOL criteria but did not contain any primary data (i.e. literature reviews, meta-analyses, modelling studies) or were stakeholder engagement or land manager survey studies were excluded with the reason given as ‘Review’. Multi-chapter publications (books, conference proceedings, research reports) were coded as such and no data extracted due to time limitations. These citations are recorded in Supplementary Table S1 (available online) and further data extraction would be possible in future synthesis work.

A1.2.1. Inclusion/exclusion criteria

The criteria used to decide whether articles should be included or excluded at title, abstract and full text screening are given below, ordered by PICOL elements (Population, Intervention, Comparator, Outcome, Location; Table 2.2).

A1.2.1.1. Population

Included

- Sheep, beef cattle, dairy cattle
- Pasture (under trees/shrubs)

Excluded

- Ruminant livestock that are not sheep or cattle (e.g. goats)
- Non-ruminant livestock (e.g. pigs, poultry)
- Studies that solely consider non-forage crops (e.g. silvoarable systems)

A1.2.1.2. Intervention

Included

- Silvopasture, shelterbelts/windbreaks, riparian strips, hedges, Dehesa/Montado, wood pasture, forest grazing, orchards, woody biofuel and farm woodlands implemented with pasture for livestock grazing as an understory or in the surrounding agricultural matrix

Excluded

- Articles that compare non-grazed forestry/afforestation with pasture; not agroforestry because not integrated
- Articles that consider woody plant/shrub encroachment onto rangeland or wholly-natural savannah systems; not agroforestry because the integration of trees and livestock is not intentional
- Riparian buffer strips that don't contain any woody perennials (e.g. grass buffers)
- Non-woody shelterbelts/windbreaks (e.g. use of tall grasses)
- Any artificial manipulations without real trees/shrubs, e.g. shade experiments using shade cloth, windbreak experiments using plastic sheets, addition of leaf litter onto pasture by humans rather than natural litter-fall

A1.2.1.3. Comparator

Included

- Pasture without trees/shrubs
- Forest without grazing

Excluded

- Unmanaged land of any form
- Forest grazing by game or wildlife rather than domestic livestock
- Comparison of two or more treatments that are not the intervention of interest (even if under an agroforestry system), e.g. different fertiliser applications, different understory species

A1.2.1.4. Outcome - Productivity

Included

- Understory/pasture productivity (e.g. dry matter production, herbage yields etc)
- Livestock mortality, growth rates, heat/cold stress, milk yield

Excluded

- Studies that just measure pasture quality (e.g. crude protein or micronutrient contents) without measuring impact on livestock growth rates o.e.
- Livestock diseases or illness made more or less likely due to proximity to trees, e.g. abortion caused by eating pine needles, increased tick burden in forest grazing
- Any articles considering consumption of tree fodder or browse by livestock
- Any articles that just consider tree growth or timber yields under different systems (unless economic implications are explicit, in which case coded under economics, below)

A1.2.1.5. Outcome - Environmental impacts

Included

- Greenhouse gas emissions: measurements of emissions or sequestration or stocks of carbon in soil or above- or below-ground plant biomass
- Flood hazard: volume of water runoff, infiltration rate of water into soil, hydraulic conductivity of soil
- Water quality: water nutrient concentrations, suspended sediments etc.
- Air quality: measurement of removal of air pollutants by trees
- Soil erosion

Excluded

- Flood hazard: measurements just of bulk density/penetration resistance/other measurement of compaction where infiltration/runoff only inferred
- Water quality: measurements just of stream fauna (e.g. macroinvertebrates) and water quality only inferred
- Air quality: impact of air pollutants (e.g. ammonia uptake or deposition) on tree health
- Other exclusion reasons
    - Salinity studies
    - Impacts or risk of fire
    - Exclusively measuring soil micro- and macrofaunal (bacteria, fungi, mycorrhizae, invertebrates including ants and dung beetles)

A1.2.1.6. Outcome - Economics

Included

- Overall profitability of
    - i) farm business with/without agroforestry, or
    - ii) forestry business with/without livestock grazing,

including measurements of value of:

- timber/non-timber tree products/biofuel,
- value of forage for livestock grazing,
- sporting benefits
- payments for ecosystem services (e.g. sale of carbon credits)

Excluded

- Livestock damage to trees in agroforest or forest
- Suppression of natural regeneration of trees by livestock grazing or value of removal of herbage by livestock to facilitate natural regeneration of trees

A1.2.1.7. Location

Included

- Temperate European countries (see search string, Appendix A.1.)
- New Zealand and temperate regions of Australia
- Temperate regions of North America (parts of Canada and the USA) and South America (parts of Chile and Argentina)

Excluded

- Tropical, sub-tropical, boreal and subarctic/sub Antarctic regions of countries in search string
    - Subarctic/boreal regions of Canada and parts of some northern European countries
    - Sub-Antarctic regions of Chile and Argentina
    - Tropical and sub-tropical regions of Australia (e.g. Queensland), USA (Texas, Oklahoma, Louisiana, Arkansas, Alabama, Mississippi, Tennessee, Kentucky, North Carolina, South Carolina, Georgia, and Florida), Chile and Argentina
- Temperate regions in countries not searched for (e.g. parts of China, India, Mexico, Turkey, Russia)

We searched for literature from countries with significant temperate agroforestry research following Gordon et al. (2018), with the exception of China and India. We chose to exclude temperate regions in countries not explicitly searched for to avoid the risk of including only part of the evidence bases from these countries. We did not search for every country with a temperate region because study region or coordinates are often not included in article metadata (keywords, title or abstract) and therefore are difficult to accurately search for using bibliographic databases and citation indexes. The alternative of including all countries with a temperate region and then excluded non-temperate studies was deemed too burdensome for a likely relatively low return of relevant studies.

A1.2.1.8. Language

Included

- English

Excluded

- All others

A1.2.1.8. Data range

Included

- All

Excluded

- n/a

A1.2.2. Article meta-data and variables coded

Fields of article meta-data and variables coded during full text screening and data extraction are given in Table A1.1. Screening information and article meta-data were coded for all articles screened at full text, whereas PICOL variables were only coded for relevant full-text articles. For the outcome variables, a coding of ‘positive’ indicates that the agroforestry treatment (i.e. the coded Intervention) resulted in a more favourable outcome than the coded Comparator (for example, improved pasture or livestock productivity, less GHGEs, more carbon sequestered, less water runoff, better water or air quality, reduced soil erosion, better enterprise economics), and vice-versa for a coding of ‘negative’, and so on.

Table A1.2. Fields of article meta-data and variables coded during full text screening and data extraction

Section	Field	Options
Screening information	Full text found? Screener Full text relevant? Exclusion reason	Yes/No/Found but can't access Review 1/Reviewer 2 Yes/No/Book/Text not in English L/P/I/C/O/Review
Article meta-data	Year published Author Title Journal Title (if applicable) ISBN/ISSN DOI Volume Issue Pages	
Location	Country State Latitude, Longitude (decimal degrees)	
Population		Sheep/Cattle/Mixture of sheep & cattle/Pasture without livestock/Unclear
Intervention[†]		Silvopasture/Shelterbelt/Windbreak/Riparian strip/Hedge/Dehesa/Montado/Wood pasture/Forest grazing/Orchard/Biofuel/Farm woodland/Multiple/Other
Comparator		Pasture without trees/Forest without grazing/Baseline from implementation/No comparator/Other
Outcome - productivity	Productivity measure	Understory or pasture production/Livestock mortality/Livestock growth/Livestock heat stress/Livestock cold stress/Milk yield/Total productivity (pasture + trees)/Multiple/Other
	Effect on productivity measure	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Decrease with increased tree density or cover or proximity/Unclear
Outcome – greenhouse gas emissions & carbon stocks/sequestration	Carbon/GHGE measure	Soil organic carbon/Soil organic matter/Total soil carbon/Belowground carbon (plant roots)/Aboveground carbon (plant stems)/Total carbon (above- and below-ground + soil)/GHGEs/Livestock offset or mitigate/Multiple/Other
	Effect on carbon/GHGE measure	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear
Other environmental outcomes	Effect on flooding/runoff/infiltration	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear

	Effect on water quality	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear
	Effect on air quality	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear
	Effect on soil erosion	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear
Outcome - economics	Effect on enterprise economics	Positive/Negative/No effect/Mixed results (positive + no effect)/Mixed results (negative + no effect)/Mixed results (positive + negative)/Unclear

† Agroforestry types were typically coded as they were described in the underlying article. Although the term 'silvopasture' is commonly used as a catch-all term for livestock agroforestry (i.e. intentionally integrating woody vegetation with livestock farming (Raskin and Osburn, 2019)) in most of the literature 'silvopasture' is used to refer more specifically to regularly-spaced trees in rows or sometimes clumps. This more specific usage is retained here and separate terms are used to refer to other types of livestock agroforestry.

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Appendix 2. Supplementary Materials for Chapter 3

A2.1. Systematic review methods

We used the Reporting standards for Systematic Evidence Syntheses to prepare this Supplementary Materials Appendix (Haddaway et al., 2017c) and developed and followed a predetermined protocol when conducting our review (unpublished). Below, we detail our two rounds of literature searching (tillage intensity first, then cover crops and ley-arable together) and screening of records by title, abstract and full text. We provide information on data extraction from relevant studies and critical appraisal, and further details of using these data for quantitative Bayesian meta-analysis. Further supporting files are provided online (Jordon, 2022).

Table A2.1. Review question elements separated by Population, Intervention, Comparator, Outcome and Location (PICOL) for each intervention of interest

PICOL element	Tillage intensity (TI)	Cover crops (CC)	Ley-arable (LA)
Population	Arable systems (including research stations, experimental plots, field trials and working farms but excluding greenhouse or laboratory experiments)		
Intervention	Any tillage practice, included no tillage (direct drilling), reduced/minimum/conservation tillage, conventional tillage (typically with use of mouldboard plough)	An arable rotation that contains a sown cover or catch crop at a least one point in the rotation between arable cash crops	An arable rotation that contains a temporary grass-based ley for one or multiple consecutive years between arable cash crops
Comparator	A different intensity of tillage	Soils or stubble left bare between annual cash crops	Continuous arable cropping or a different ley duration
Outcomes	Soil organic carbon (SOC), soil organic matter (SOM) or soil total carbon (StC) where soils are shown to be free of carbonates, either as a concentration (g/100g) or stock (t/ha) Crop yield (t/ha)		
Location	Regions with temperate oceanic climate with no dry season and warm summer (i.e. Köppen–Geiger climate classification Cfb (Peel et al., 2007)), restricted to countries that are exclusively Cfb (Britain including Ireland, Belgium, Netherlands, Luxembourg, New Zealand) or have substantial Cfb regions (France, Germany, Spain, Denmark, Australia).		

A2.1.1. Search strategy

We carried out the tillage search first, followed by the cover crops and ley-arable searches together due to the similarity between the search terms (Table A2.2). Searches were conducted for “All years” in bibliographic databases and citation indices, with search results from Haddaway et al. (2015) excluded in Endnote X9 before citation screening to prevent duplication of effort. This approach was taken because we added the bibliographic database CAB Abstracts to our search strategy to capture relevant citations missed by the previous searches. We included relevant records from the previous searches of Haddaway et al. (2015), (Haddaway et al., 2017a) in our data extraction (Section A2.1.3). We did not estimate the comprehensiveness of the search here as the search string had previously been refined to achieve this when developed by Haddaway et al. (2015), (Haddaway et al., 2017a).

We did not specifically search for grey literature and only included studies published in English in our database, but we are confident that this is unlikely to have biased our results as grey literature is unlikely to report sufficient data for inclusion in meta-analysis and most published literature in our geographic region of interest is in English, as found by Haddaway et al. (2017a). Although separate literature searches for studies that measured SOC or yield would have resulted in more data for analysis, this would have disproportionally increased the volume of literature for screening and running a multi-variate analysis using only paired observations of soil carbon and yield was central to testing our hypotheses. We did not include studies from other climatic zones, to maximise the generalisability of our findings to the context of interest and to enable use of these data in parametrising a spatially explicit soil carbon model at a national scale in future work (Jordon et al., 2022a).

For cover crops and ley-arable, we conducted title screening of the reference lists of relevant reviews and meta-analysis. A list of citations identified as having relevant titles is available online (Jordon, 2022), along with information of whether the record abstract is relevant and full text downloaded for inclusion in full text screening.

Table A2.2. Search strategy for systematic review

	Tillage (NT)	**Cover crops (CC)**	**Ley-arable (LA)**
Systematic search updated	2015 search, Haddaway et al. (2017a)	2013 search, Haddaway et al. (2015)	
Search string	Appendix 2.1.1.1	Appendix 2.1.1.2	

Bibliographic databases and citation indexes	Web of Science:
	• Web of Science Core Collection (1900–present)
	    ○ Science Citation Index Expanded (1900–present)
	    ○ Social Sciences Citation Index (1900–present)
	    ○ Arts & Humanities Citation Index (1975–present)
	    ○ Conference Proceedings Citation Index-Science (1990–present)
	    ○ Conference Proceedings Citation Index-Social Science & Humanities (1990–present)
	    ○ Book Citation Index–Science (2005–present)
	    ○ Book Citation Index–Social Sciences & Humanities (2005–present)
	    ○ Emerging Sources Citation Index (2015–present)
	    ○ Current Chemical Reactions (1986–present) (includes *Institut National de la Propriete Industrielle* structure data back to 1840)
	    ○ Index Chemicus (1993–present)
	• BIOSIS Citation Index (1969–present)
	• Current Contents Connect (1998–present)
	• Data Citation Index (1993–present)
	• Derwent Innovations Index (1993–present)
	• KCI-Korean Journal Database (1980–present)
	• MEDLINE® (1950–present)
	• Russian Science Citation Index (2005–present)
	• SciELO Citation Index (2002–present)
	• Zoological Record (1993–present)
	CAB Abstracts
	Scopus		

Search dates	21 July 2020	12 Jan 2021	
Search date range	2015 onwards for Web of Science and Scopus, as updating 2015 search from Haddaway et al. (2017a); all years for CAB Abstracts as not previously searched by Haddaway et al. (2017a)	All years	

Grey literature searched	None	
Languages searched	English	
Snowballing from previous reviews and meta-analysis	No	Yes, title-relevant citations from reviews and meta-analyses provided online (Jordon, 2022).

For the tillage search, Location terms were not included in the search string, as we were concerned that this would lead to relevant citations being missed. However, due to the high resource requirements of screening large numbers of non-relevant citations, for the cover crop and ley-arable search, we ran the search both with and without Location terms. These returned 3025 and 14,753 citations respectively. We screened a random sample of 600 (appox. 5%) from the 11,728 citations returned by the ‘without Location’ search but missed by the ‘with location’ search. We identified no relevant full texts from this random sample and so estimate that less than 1 in 600 (i.e. <0.17%) of the 11,728 would be relevant at full text. As such, we only screening the results from the ‘with Location’ search due to the low chance of missing relevant citations.

A2.1.1.1. Tillage search string

soil*

AND

arable OR agricult* OR farm* OR crop* OR cultivat*

AND

till* OR “no till*” OR “reduced till*” OR “direct drill*” OR “conservation till*” OR “minimum till*”

AND

“soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM OR “carbon sequestrat*” OR “C sequestrat*”

AND

yield* OR harvest* OR return* OR performance OR productivity OR production

Groups of terms between AND operators searched by “Topic” field in Web of Science, “TITLE-ABS-KEY” in Scopus and “All fields” in CAB Abstracts. No location terms in search string.

A2.1.1.2. Cover crop and ley-arable search string

<u>Web of Science</u>

TS=(soil*)

AND

TS=(arable OR agricult* OR farm* OR crop* OR cultivat*)

AND

TS=(rotat* OR “break crop*” OR grass* OR clover OR clovers OR ley* OR legum* OR “cover crop*” OR “grass clover” OR “crop* system*” OR fallow* OR “set*aside” OR “catch*crop*” OR intercrop* OR “green manur*” OR perennial* OR “mixed farm*” OR “fertility build*” OR “under*sow*”

OR

sheep OR ewe* OR lamb OR lambs OR "Ovis aries" OR ovine OR “Bos taurus” beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR

steers OR heifers OR calf OR calves OR bovine OR ruminant OR ruminants OR livestock

OR

grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR herbage OR sward* OR “sod based” OR hay OR silage OR forag* OR fodder OR cut OR cutting)

AND

TS=(“soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM OR “carbon sequestrat*” OR “C sequestrat*”)

AND

TS=(yield* OR harvest* OR return* OR performance OR productivity OR production OR biomass)

AND

TS=(UK OR “United Kingdom” OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR France OR French OR Germany OR German OR Belgium OR Belgian OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR “New Zealand”)

Scopus

TITLE-ABS-KEY(soil*)

AND

TITLE-ABS-KEY(arable OR agricult* OR farm* OR crop* OR cultivat*)

AND

TITLE-ABS-KEY(rotat* OR “break crop*” OR grass* OR clover OR clovers OR ley* OR legum* OR “cover crop*” OR “grass clover” OR “crop* system*” OR fallow* OR “set*aside” OR “catch*crop*” OR intercrop* OR “green manur*” OR perennial* OR “mixed farm*” OR “fertility build*” OR “under*sow*”

OR

sheep OR ewe* OR lamb OR lambs OR "Ovis aries" OR ovine OR “Bos taurus” beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR bovine OR ruminant OR ruminants OR livestock

OR

grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR herbage OR sward* OR “sod based” OR hay OR silage OR forag* OR fodder OR cut OR cutting)

AND

TITLE-ABS-KEY(“soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM OR “carbon sequestrat*” OR “C sequestrat*”)

AND

TITLE-ABS-KEY(yield* OR harvest* OR return* OR performance OR productivity OR production OR biomass)

AND

TITLE-ABS-KEY(UK OR “United Kingdom” OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR France OR French OR Germany OR German OR Belgium OR Belgian OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR “New Zealand”)

CAB Abstracts

All Fields: (soil$)

AND

All Fields: (arable OR agricult$ OR farm$ OR crop$ OR cultivat$)

AND

All Fields: (crop rotat$ OR break crop$ OR grass$ OR clover OR clovers OR ley$ OR legum$ OR cover crop$ OR grass clover OR crop$ system$ OR fallow$ OR set$ aside OR catch$ crop$ OR intercrop$ OR green manur$ OR perennial$ OR mixed farm$ OR fertility build& OR under$ sow$ OR sheep OR ewe OR ewes OR lamb OR lambs OR Ovis aries OR ovine OR Bos taurus beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR bovine OR ruminant OR ruminants OR livestock OR grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR herbage OR sward$ OR sod based OR hay OR silage OR forag$ OR fodder OR cut OR cutting)

AND

All Fields: (soil organic carbon OR soil carbon OR soil C OR soil organic C OR SOC OR carbon pool OR carbon stock OR carbon storage OR soil organic matter OR SOM OR carbon sequestrat$ OR C sequestrat$)

AND

All Fields: (yield$ OR harvest$ OR return$ OR performance OR productivity OR production OR biomass)

AND

Title OR Abstract OR Descriptor Index: (UK OR United Kingdom OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR France OR French OR Germany OR German OR Belgium OR Belgian OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR New Zealand)

A2.1.2. Article screening

Title and abstract screening of Tillage citations was conducted in the online platform sysrev, to allow consistency of screening decisions to be easily checked. MWJ and NRH double-screened citations in batches of 50, discussing and resolving disagreements, until the agreement threshold of a Cohen's kappa score of 0.6 was exceeded (after 150 double-screened citations in total), at which point MWJ single-screened the remainder of the citations. Title and abstract screening of Cover crop and ley-arable citations was carried out by MWJ in MS Excel, having previously established a consistency in screening decisions with NRH for tillage studies. Article full texts were searched for in Google Scholar, Web of Science and the University of Oxford's online library portal. Citations for full texts that could not be found are provided online (Jordon, 2022). All full text screening was carried out in MS Excel by MWJ, with one exclusion reason given per article in the order of Population, Intervention, Comparator, Outcome, Location, Duplicate or Review article, available online (Jordon, 2022). Inclusion and exclusion criteria for title, abstract and full text screening are given in Table A2.3.

Table A2.3. Inclusion and exclusion criteria for title, abstract and full text screening of articles identified by systematic literature search.

	Tillage (NT)	Cover crops (CC)	Ley-arable (LA)
Population	*Included*: Arable systems, including research stations, experimental plots, field trials and working farms *Excluded*: greenhouse, pot or laboratory experiments		
Intervention	*Included*: all tillage practices, including: no-tillage (also described as direct drill); reduced, minimum or conservation tillage (i.e. chisel plough, disc plough, harrow, mulch plough, ridge till); conventional tillage (i.e. mouldboard plough); subsoiling.	*Included*: an arable rotation that contains a sown cover or catch crop at a least one point in the rotation between arable cash crops *Excluded*: fallow-only with no cover or cash crop explicitly sown	*Included*: an arable rotation that contains a temporary grass-based ley for one or multiple consecutive years between arable cash crops *Excluded*: studies where long term permanent pasture is one-off converted to arable, or long term continuous cropping arable is converted pasture; treatment must have both ley and arable components in rotation
Comparator	*Included*: a treatment with a different tillage regime or intensity (e.g. depth of tillage, different mechanical implement used), with all other aspects of the treatment remaining the same (or factorial treatments) *Excluded*: multiple aspects of the treatment differed in a non-factorial manner, or no comparator	*Included*: an arable rotation with a different frequency of cover or cash crop inclusion that is otherwise identical or very similar *Excluded*: multiple aspects of the treatment differed in a non-factorial manner, or no comparator	*Included*: an arable rotation that is similar but does not contain a temporary ley, or an arable rotation with a temporary ley of a different duration *Excluded*: multiple aspects of the treatment differed in a non-factorial manner, or no comparator
Outcomes	*Included*: Soil organic carbon, soil organic matter or soil total carbon (where soils are shown to be free of carbonates), either as a concentration (g/100g) or stock (t/ha) *Excluded*: studies that only present other chemical, physical or biological properties of soil		
	Included: combinable crop grain yield (t/ha), or root yield in the case of potatoes, sugar beet etc. *Excluded*: studies that only present other properties of crop, such as growth rates		
Location	*Included*: studies in the British Isles (including Ireland), Belgium, Netherlands, Luxembourg and New Zealand (entirely temperate oceanic climate, Cfb Köppen-Geiger classification, Peel et al. 2007). Also studies in Cfb regions of France, Germany, Spain, Denmark and Australia. Excluded: studies in non-Cfb regions of France, Germany, Spain, Denmark and Australia. Initial conservative exclusion from specification of study climate in title, abstract or full text, and inspection of study location for Spain and Australia. Full exclusion using Peel et al. Köppen-Geiger raster and study degrees decimal coordinates.		

A2.1.3. Data extraction and critical appraisal

Data was extracted directly from relevant studies to a predefined data extraction form in MS Excel by MWJ, who checked for errors and consistency of coding decisions during extraction. The complete spreadsheet of extracted data from relevant studies is provided in the SI Dataset. Study critical appraisal was carried out alongside data extraction using a scoring system based on Haddaway et al. (2017a)(Table A2.4).

Table A2.4. Critical appraisal criteria used to score relevant studies, adapted from Haddaway et al. (2017a)

Variable	Value	Score‡
Spatial (true) replication	1 replicate	-1†
	2 replicates	0
	3-4 replicates	1
	> 4 replicates	2
Temporal replication	≤ 3 replicates	0
	4-6 replicates	1
	> 6 replicates	2
Treatment allocation	Purposive (selective)	0
	Split-plot/latin square/ blocked/randomised	2
Duration of experiment (years)	< 5	-2†
	5-9	-1†
	10-19	0
	20-29	1
	≥ 30	2
Soil sampling depth	Shallow (≤ 15 cm) sampling	0
	Plough layer (maximum depth 15–25 cm) single or multiple sampling, or deep (maximum depth > 25 cm) single sampling	1
	Multiple deep sampling (maximum depth > 25 cm)	2

‡ Where insufficient information is given to assign a score, a “?” is used
† Negative scores introduced here to capture studies previously excluded by Haddaway et al. (2017a) in particular because we did not require study duration to be 10+ years for inclusion.

Following the method of Haddaway et al. (2017a), the critical appraisal scores for spatial replication and treatment allocation were summed. Scores of 3 or 4 were assigned ‘high’ validity and while those of 2 or less were assigned ‘low’ validity. All studies were included in the meta-analysis, but a sensitivity analysis was conducted

excluding studies of low and unclear validity to check if this influenced model output and interpreted accordingly.

Where additional calculations for producing usable data for analyses were required, these were carried out in individual spreadsheets, available online (Jordon, 2022). Extra calculations undertaken are recorded in the main datasheet and only the calculated data are retained here. The methods for these calculations are given in Table A2.5.

Table A2.5. Additional calculations required when extracting data from studies

Operation	**Method**	**Further details**
Extracting data from article figures when not available in tables	Used free online tool WebPlotDigitiser version 4.4	
Pool either SOC or yield data when presented factorially across a non-interest treatment but the other data (yield or SOC, respectively) is not	*rma* function in *metafor* package, implemented in R version 4.0.3	Calculates weighted mean and standard error, taking means with standard errors as input
Convert soil organic matter (SOM to soil organic carbon (SOC)	$SOC = \frac{SOM}{1.724}$	After Haddaway et al. (2017a)
Convert SOC stocks (t/ha) to SOC concentration (g/100g)	$SOC\ conc\ (g/100g) = \frac{SOC\ stock\ (ha)}{Bulk\ density\ (g/cm^3)\ x\ Soil\ depth\ (cm)}$	After Haddaway et al. (2017a)
Convert standard deviation (SD) to standard error (SE)	$SE = \frac{SD}{\sqrt{n}}$	Where *n* is the number of samples. After Haddaway et al. (2017a)
Convert confidence interval (CI) to standard error (SE)	$SE = \frac{CI}{t}$	Where *t* is the appropriate value from t-table. After Haddaway et al. (2017a)
Convert least significant difference (LSD) to standard deviation (SD)†	$SD = \sqrt{\frac{\left(\frac{LSD}{t}\right)^2}{\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}$ $df_t = a.b.c.(n-1)$	Where a x b x c is the number of levels of each factor used in the analysis producing the LSD. After Haddaway et al. (2017a)
Estimate standard deviation (S)† from box plots	$S \approx \frac{1}{2}\left(\frac{b-a}{\xi(n)} + \frac{q_3 - q_1}{\eta(n)}\right)$	After (Wan et al., 2014), where *a* is the minimum value, *b* is the maximum value, q_1 is the first quartile, q_3 is the third quartile, *n* is the sample size, and

		the two constants are available from Tables 1 and 2 in Wan *et al*. respectively.
Estimate standard deviation (SD)† from range	$SD \approx f\ x\ range$	After (Walter and Yao, 2007), where *f* is a conversion factor from Table 1 in Walter & Yao.
† Subsequent conversion to standard error (SE) given above.		

When categorising tillage treatment, full inversion tillage (typically with a mouldboard plough) was classed as 'conventional tillage', direct drilling with no soil disturbance was classed as 'no tillage', and intermediate measures that involved some degree of non-inversion soil disturbance were coded as 'reduced tillage'. We did not encounter chisel tillage deeper than 40 cm which has previously been classed alongside mouldboard ploughing as high-intensity tillage (Haddaway et al., 2017a). Our categorisations usually agreed with the terms used in the original publications. Where a range was given for tillage depth (e.g. 25-30cm) the deepest of these was recorded, to be conservative.

Where error or variability values were clearly for between treatments rather than within treatments, these were not extracted as they do not relate to the error term of interest.

Some studies had a factorial design, where one of the interventions in the factorial design met our inclusion criteria but the other intervention/s did not. Where results were presented separately for each factor, only those for the intervention of interest were extracted. However, where results were presented factorially across intervention combinations, we extracted all data and let the meta-analysis model pool across the non-target factors (rather than pooling manually in advance), i.e. the

model estimated the effects of interest across multiple observations that differed due to interventions not included in the analysis as predictors.

Where multiple articles were captured by the search that presented data for the same study, the citation and Unique article ID from the most recent study were used, and other articles were coded as 'duplicate' and their citations recorded in the datasheet. Similarly, where articles referred to previous articles for information about the same study, these were found where possible and their citations also recorded in the datasheet.

A2.1.4. Requests for missing data

Where desired data was missing from studies (Table A2.6), we contacting the corresponding author of the article, using the following template:

Dear Dr/Prof [name],

I am a PhD student at the University of Oxford. I am conducting a systematic review (following Collaboration for Environmental Evidence guidelines) on the soil carbon and yield impacts of adopting no- or reduced tillage, cover crops, and ley-arable rotations in temperate arable systems, in collaboration with Prof Pete Smith and Dr Neal Haddaway.

I am including your study "[title]" published in [year] in the meta-analysis, and am contacting you to request if you could please provide some additional information to fully parametrise the analysis.

In particular, do you have any information on [delete as appropriate]

- Study site soil clay content (%)
- Study site soil bulk density (g/cm^{-3})
- Baseline (i.e. pre-intervention) measurement of the soil organic carbon (g/kg or t/ha) and corresponding standard deviation/error
- Within-treatment estimates of the variation associated with soil carbon measurements presented in the paper (standard deviation or standard error)
- Baseline (i.e. pre-intervention) measurement of crop yields (t/ha) and corresponding standard deviation/error
- Within-treatment estimates of the variation associated with crop yield measurements presented in the paper (standard deviation or standard error)
- What do the error values presented for soil carbon and/or yield correspond to (are these standard error, standard deviation, least significant difference, or other)?
- The number of soil samples used to calculate the mean estimates and error values presented in the study (i.e. what is 'n' for these values)

I would be very grateful if you could send me any of this information and would include you in the acknowledgments of the paper when written up. I am happy to get information from other published research articles where applicable if you could point

me to these. It would also be useful to know if these data were not measured in your study or you no longer have access to the data.

Thank you very much.

Best wishes,

Matt

We thank authors who responded in the Acknowledgments of Chapter 3.

Table A2.6. Required data missing from studies. P: information provided in study article, M: information missing from study article, MP: information missing from study article but provided by author upon contact.

Unique Study ID	Clay (%)	Bulk density	SOC baseline	SOC baseline error	SOC endline error	Yield endline error
2021RGHL_CCLANT025	P	M	P	M	MP	MP
2021RGHL_CCLANT029	M	M	M	M	P	P
2021RGHL_CCLANT029	M	M	M	M	P	M
2020UPDTCCLA003	P	P	P	P	MP	M
2020UPDTCCLA037_ 2016UPDT014	P	P	P	P	P	M
2020UPDTCCLA061a	P	P	P	M	M	M
2020UPDTCCLA061c	P	P	P	M	M	M
2020UPDTCCLA071	P	P	M	M	P	P
2020UPDTCCLA072	P	P	P	M	M	M
2020UPDTCCLA074a	MP	MP	M	M	P	P
2020UPDTCCLA074b	MP	M	M	M	P	P
2020UPDTCCLA074c	MP	M	M	M	P	P
2020UPDTCCLA081	M	M	P	M	M	P
2020UPDTCCLA114	P	P	P	P	P	P
2020UPDTCCLA116	P	P	P	P	P	MP
2020UPDTCCLA136	P	MP	M	M	P	M
2020UPDTCCLA136	P	M	M	M	M	M
2020UPDTCCLAsnowball161a	M	P	M	M	P	M
2020UPDTCCLAsnowball161b	M	P	M	M	P	M
2020UPDTCCLAsnowball161c	M	P	M	M	P	M
2020UPDTCCLAsnowball162_ THOMS04V20.1	P	P	M	M	P	M
2020UPDTCCLAhdwymissed184	P	M	M	M	M	M

TAYLO06V144.2a	M	M	M	M	M	P
TAYLO06V144.2b	M	M	M	M	M	P
BROCK11V174.3	M	M	M	M	P	P
2020UPDT006	P	P	M	M	P	P
2020UPDT011	P	P	P	M	M	P
2020UPDT012	P	P	M	M	M	P
2020UPDT038	P	P	M	M	P	P
2020UPDT043a	M	M	MP	MP	M	M
2020UPDT043b	M	M	MP	MP	M	M
2020UPDT043c	M	M	MP	MP	P	M
2020UPDT058a	M	P	P	M	M	P
2020UPDT058b	M	P	P	M	M	P
2020UPDT066	P	M	M	M	M	M
2020UPDT070	P	MP	M	M	P	P
2020UPDT126	P	MP	P	P	P	P
2020UPDT199	M	P	M	M	P	M
10245926	P	P	M	M	P	P
2016UPDT018b	MP	P	M	M	M	M
2016UPDT018c	MP	P	M	M	M	M
2016UPDT018e	MP	P	M	M	M	M

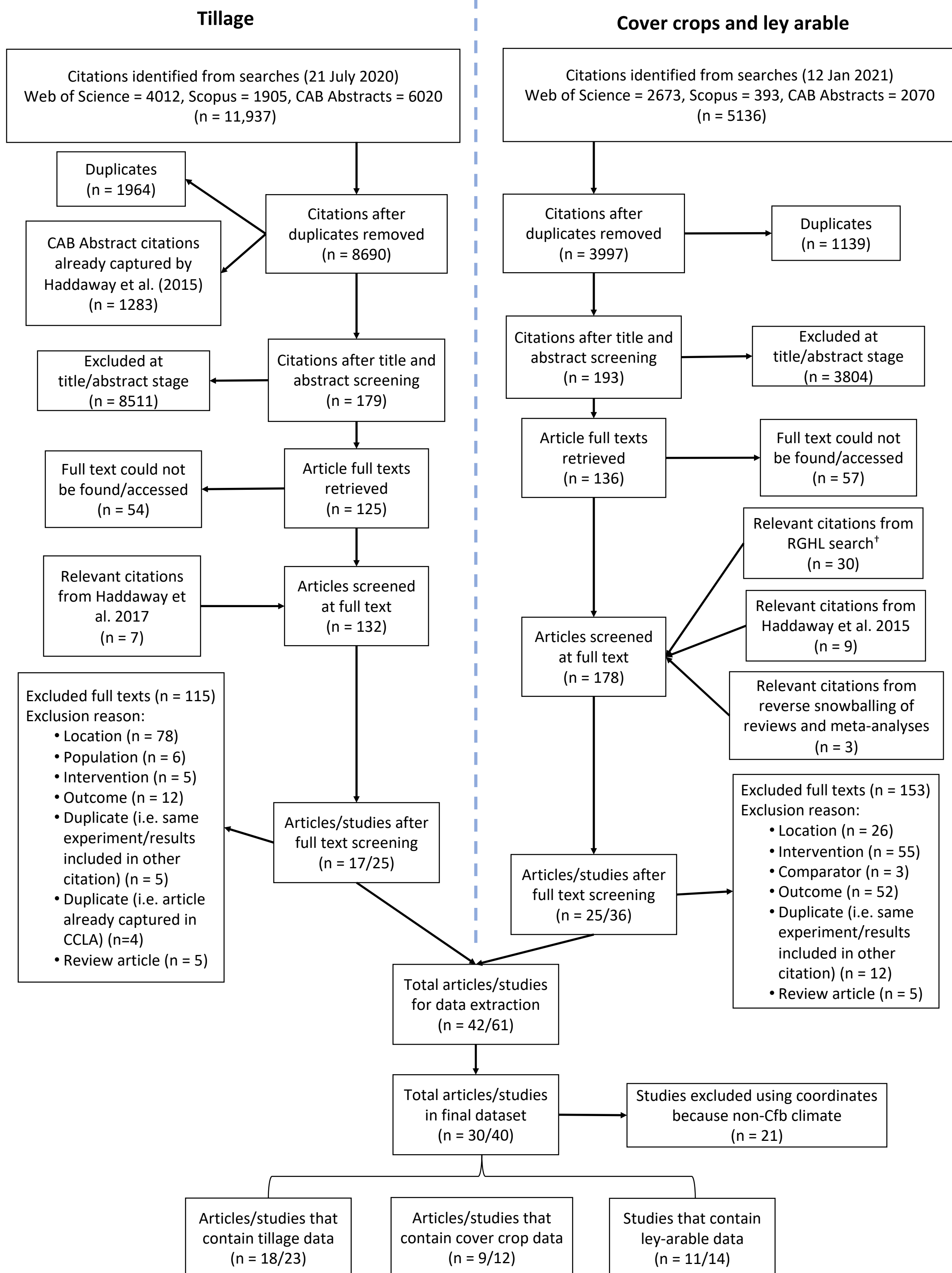

Figure A2.1. The literature searching and screening process, with the number of records included and excluded at each stage. For articles excluded at the full text screening stage, the number excluded for each reason are also given. This flow chart follows the template of (Haddaway et al., 2017b). † RGHL search undertaken for a separate meta-analysis following similar systematic review

methods of rotational grazing and herbal ley interventions in temperate oceanic regions (Jordon et al., 2022b).

A2.2. Bayesian meta-regression methods

Because we included tillage, cover crop and ley-arable interventions in the same analyses, where studies were not explicit about any of these regimes, we assumed 'conventional' practice as the default (i.e. conventional tillage, no cover crops, and no ley phase in arable rotation). In particular, some ley-arable and cover crop studies did not specify tillage regime. When we included 'not specified' as a level in the tillage intensity categorical predictor, this was not significantly different to the 'conventional tillage' level, which gives us confidence that this is a suitable approach.

Although we extracted data on intervention-specific predictors such as tillage depth, cover crop composition, and ley management, we lacked observations to robustly include these in intervention-specific analyses. Because no studies presented true baseline data for yield, we were unable to include this as a predictor. We did not include study site as a nested random factor with Unique study ID, because there were few sites with multiple studies in our dataset. We did not conduct a depth-distributed analysis for tillage studies as in Haddaway et al. (2017a) as we were primarily interested in the overall impact of interventions on SOC and including multiple sampling depths per study treatment was not possible in a multivariate analysis with yield.

Analysing all three interventions together in one model rather than fitting individual models is robust to Simpson's Paradox (where an effect seen in sub-groups of data disappears or reverses when groups are combined) 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. Our analysis assumes that the effects of the interventions considered here (tillage, cover crops and ley-arable) on SOC and yield are constant across studies. Although we attempted to test this assumption by including intervention predictors within the random effects term, we have insufficient data points to identify a model of this complexity.

A2.2.1. Model fitting

We used default priors of brms in our models, which are designed to be only weakly informative or uninformative as to have negligible impact on the results. We specify the priors used by the models in an additional file online (Jordon, 2022), and give further details of model sampling in Table A2.7. We made the assumption that within-treatment standard errors were known, which although arguably inconsistent since they are in fact also measured with error, is standard practice in both Bayesian and frequentist meta-analyses, and approaches relaxing this assumption have only been constructed for the most simple meta-analytic models where they do not lead to noticeably improved model performance (Malzahn et al., 2000). We checked model convergence using the Rhat parameter and ensured effective sample size measures were sufficiently large (Vehtari et al., 2020). Model non-convergence was addressed by increasing the number of iterations for sampling and divergent transitions were addressed by decreasing the sampler step size (Stan Development Team, 2020). Both between- and within-study heterogeneity was modelled in the

form of corresponding standard deviation parameters (across studies, and across effect sizes within studies, respectively).

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 (Intercept), with 95% Credible Intervals. The same plots showing Predictive Intervals are shown in Fig A2.5. We also displayed the raw SOC and Yield data from the underlying studies for each intervention using the *forestplot* package (Gordon and Lumley, 2020). 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* (defined in main text Methods). To investigate potential publication bias, we conducted Egger's regression tests for funnel plot asymmetry using the *regtest* function in *metaphor* (Viechtbauer, 2010) and present the results from this along with funnel plots of endline SOC and yield effect sizes against their standard errors (Appendix A2.2.3). However, we do not interpret these results further, as there are multiple potential sources of funnel plot asymmetry in our data due to the extensive heterogeneity in the included studies both methodologically and treatment-wise. This renders publication bias only one possible explanation for funnel plot asymmetry, making this test potentially misleading in either direction.

Table A2.7. Details of brm sampling when fitting models				
Model	Chains	Iterations‡	Warmup samples‡	Total post-warmup samples
EP	4	2000	1000	4000
EI	40†	2000	1000	40000
EIBP	40†	8000	4000	160000
EIBI	40†	8000	4000	160000
‡per chain †4 chains per imputed dataset, 10 imputed datasets				

A2.2.2. Model summaries

1. EP

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Clay_all_centred +
Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID)
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred +
Yield_endline_crop + (1 | a | Unique_study_ID)
   Data: NTCCLA_SOC_yield_error_centred (Number of observations: 66)
  Draws: 4 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 4000

Group-Level Effects:
~Unique_study_ID (Number of levels: 16)
                                                   Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                              0.45      0.12     0.29     0.73 1.00     1251     1736
sd(Yieldendlineesttha_Intercept)                       1.20      1.02     0.04     3.81 1.00     1761     2107
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)    0.03      0.57    -0.95     0.96 1.00     3472     2631

Population-Level Effects:
                                                   Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                                  1.52      0.12     1.28     1.76 1.00     1109     1755
Yieldendlineesttha_Intercept                          70.98      3.55    63.93    77.93 1.00     1479     1731
Cendlineest_Tillage_catNT                              0.11      0.04     0.03     0.18 1.00     5453     2988
Cendlineest_Tillage_catRT                              0.10      0.04     0.02     0.18 1.00     5980     3244
Cendlineest_Cover_crop_proportion                      0.07      0.07    -0.06     0.20 1.00     5833     2334
Cendlineest_Ley_duration                               0.04      0.01     0.01     0.06 1.00     7315     3041
Cendlineest_Study_duration_centred                     0.00      0.00    -0.01     0.01 1.00     6187     3080
Cendlineest_Latitude_centred                           0.05      0.04    -0.05     0.13 1.00     1201     1744
Cendlineest_Clay_all_centred                          -0.02      0.02    -0.07     0.01 1.00      995     1495
Cendlineest_Lower_soil_sampling_depth_cm_centred      -0.05      0.02    -0.10     0.00 1.00      956     1675
Yieldendlineesttha_Tillage_catNT                      -1.85      2.28    -6.36     2.53 1.00     5058     3040
Yieldendlineesttha_Tillage_catRT                      -0.70      2.42    -5.39     4.11 1.00     4952     3015
Yieldendlineesttha_Cover_crop_proportion              -1.72      3.78    -9.01     5.59 1.00     2608     2966
Yieldendlineesttha_Ley_duration                        0.23      0.50    -0.75     1.23 1.00     5439     3222
Yieldendlineesttha_Study_duration_centred             -0.29      0.20    -0.67     0.12 1.00     3169     2292
Yieldendlineesttha_Latitude_centred                    0.14      0.61    -1.03     1.34 1.00     1957     2387
Yieldendlineesttha_Yield_endline_cropBarley          -62.39      8.23   -78.41   -46.52 1.00     1623     1725
Yieldendlineesttha_Yield_endline_cropDurumwheat      -66.92      5.61   -77.80   -55.73 1.00     1679     2264
Yieldendlineesttha_Yield_endline_cropMaize           -58.03      3.88   -65.76   -50.37 1.00     1704     2236
Yieldendlineesttha_Yield_endline_cropMix:springwheatMfababean  -67.57      4.82   -77.33   -57.97 1.00     2667     2450
Yieldendlineesttha_Yield_endline_cropSpringbarley    -70.52      4.40   -79.26   -62.09 1.00     2296     2282
Yieldendlineesttha_Yield_endline_cropSpringwheat     -67.97      3.42   -74.68   -61.25 1.00     1913     2434
Yieldendlineesttha_Yield_endline_cropSugarbeet        22.66      5.08    12.31    32.50 1.00     2782     2557
Yieldendlineesttha_Yield_endline_cropTriticale       -65.96      4.79   -75.66   -56.80 1.00     1717     1875
Yieldendlineesttha_Yield_endline_cropWinterwheat     -63.48      4.40   -72.63   -54.85 1.00     1552     1794

Family Specific Parameters:
                       Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest          0.07      0.01     0.05     0.09 1.00     2640     3111
sigma_Yieldendlineesttha   5.10      0.55     4.14     6.29 1.00     4350     3004

Residual Correlations:
                                       Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)     0.33      0.14     0.03     0.57 1.00     4313     3163

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

2. EI

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Clay_all_centred + Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID)
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Yield_endline_crop + (1 | a | Unique_study_ID)
   Data: NTCCLA_SOC_yield_ErrorBase_IMPUTED (Number of observations: 195)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_study_ID (Number of levels: 40)
                                                      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                                 0.86      0.11     0.67     1.11 1.00    14175    22211
sd(Yieldendlineesttha_Intercept)                         11.48      1.57     8.90    15.00 1.00    19522    27913
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)   0.17      0.19    -0.22     0.52 1.00    25590    26417

Population-Level Effects:
                                                                    Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                                                   1.75      0.14     1.47     2.02 1.00    13435    20126
Yieldendlineesttha_Intercept                                           12.67      3.31     6.01    19.06 1.00    21972    26706
Cendlineest_Tillage_catNT                                               0.06      0.03     0.00     0.11 1.01     5333    29471
Cendlineest_Tillage_catRT                                               0.09      0.03     0.03     0.14 1.02     1678    30887
Cendlineest_Cover_crop_proportion                                       0.06      0.03    -0.01     0.13 1.00     8814    29424
Cendlineest_Ley_duration                                                0.05      0.01     0.03     0.08 1.02     1452     4270
Cendlineest_Study_duration_centred                                      0.00      0.00    -0.00     0.00 1.03      836    12347
Cendlineest_Latitude_centred                                            0.04      0.04    -0.04     0.12 1.02     1992    20884
Cendlineest_Clay_all_centred                                           -0.04      0.02    -0.08     0.00 1.03      737     6479
Cendlineest_Lower_soil_sampling_depth_cm_centred                       -0.06      0.02    -0.09    -0.02 1.00    18265    24419
Yieldendlineesttha_Tillage_catNT                                       -0.85      0.78    -2.37     0.68 1.00    63764    33444
Yieldendlineesttha_Tillage_catRT                                       -0.46      0.75    -1.93     1.00 1.00    63847    32935
Yieldendlineesttha_Cover_crop_proportion                                0.09      0.98    -1.83     2.03 1.00    64515    30175
Yieldendlineesttha_Ley_duration                                         0.20      0.29    -0.38     0.77 1.00    71332    30982
Yieldendlineesttha_Study_duration_centred                              -0.05      0.05    -0.16     0.06 1.00    68169    31482
Yieldendlineesttha_Latitude_centred                                     0.33      0.62    -0.87     1.59 1.00    24468    26890
Yieldendlineesttha_Yield_endline_cropAveragedMgrainequivalentkgDha     -7.30     12.08   -30.82    16.72 1.00    53091    30431
Yieldendlineesttha_Yield_endline_cropBarley                            -3.63      3.08    -9.69     2.36 1.00    35357    32469
Yieldendlineesttha_Yield_endline_cropDurumwheat                        -7.45     12.56   -32.11    17.54 1.00    48511    30876
Yieldendlineesttha_Yield_endline_cropMaize                              2.71      5.81    -8.50    14.34 1.00    27248    27938
Yieldendlineesttha_Yield_endline_cropMix:springwheatMfababean         -10.93      7.18   -24.86     3.21 1.00    23689    27415
Yieldendlineesttha_Yield_endline_cropSpringbarley                      -4.34      2.89   -10.08     1.21 1.00    35930    32114
Yieldendlineesttha_Yield_endline_cropSpringoats                       -14.96     11.39   -37.00     7.71 1.00    31823    30635
Yieldendlineesttha_Yield_endline_cropSpringwheat                       -9.68      6.71   -22.53     3.80 1.00    22826    26409
Yieldendlineesttha_Yield_endline_cropSugarbeet                         77.04      7.23    62.92    91.42 1.00    23912    27476
Yieldendlineesttha_Yield_endline_cropTriticale                         -9.46     11.85   -32.59    13.96 1.00    53737    29917
Yieldendlineesttha_Yield_endline_cropWheat                             -6.75     10.56   -27.12    14.24 1.00    32959    30105
Yieldendlineesttha_Yield_endline_cropWinterbarley                     -11.95      9.80   -31.09     7.47 1.00    34418    29489
Yieldendlineesttha_Yield_endline_cropWinterwheat                       -2.99      2.42    -7.76     1.71 1.00    35692    30598

Family Specific Parameters:
                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest            0.10      0.01     0.08     0.12 1.27      106      247
sigma_Yieldendlineesttha     2.99      0.20     2.63     3.40 1.00    31189    31112

Residual Correlations:
                                        Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)      0.15      0.08    -0.01     0.31 1.00    55070    33362

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

3. EIBP

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + C_baseline_est_centred + Clay_all_centred + Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID)
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Yield_endline_crop + (1 | a | Unique_study_ID)
   Data: NTCCLA_SOC_yield_base_Error_IMPUTED (Number of observations: 79)
  Draws: 40 chains, each with iter = 8000; warmup = 4000; thin = 1;
         total post-warmup draws = 160000

Group-Level Effects:
~Unique_study_ID (Number of levels: 14)
                                                      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                                 0.34      0.10     0.21     0.58 1.00    46535    64368
sd(Yieldendlineesttha_Intercept)                          3.43      1.10     1.81     6.05 1.00    72179    95596
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)  -0.55      0.42    -0.99     0.49 1.02     1264     7102

Population-Level Effects:
                                   Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                  1.30      0.11     1.08     1.51 1.01     3153    13497
Yieldendlineesttha_Intercept           9.28      2.89     3.38    14.88 1.00    51867    68758
Cendlineest_Tillage_catNT              0.07      0.04     0.00     0.14 1.08      290     1489
Cendlineest_Tillage_catRT              0.02      0.03    -0.05     0.09 1.03      854     2578
Cendlineest_Cover_crop_proportion      0.06      0.04    -0.02     0.15 1.02     1513     1491
Cendlineest_Ley_duration               0.05      0.02     0.02     0.08 1.09      270     1160
Cendlineest_Study_duration_centred     0.00      0.00    -0.00     0.00 1.01   208091    16819
Cendlineest_Latitude_centred           0.03      0.03    -0.04     0.09 1.02     1130     2962
```

```
Cendlineest_C_baseline_est_centred                 0.78      0.19     0.36     1.13 1.03      724     2647
Cendlineest_Clay_all_centred                       0.01      0.02    -0.05     0.05 1.04      580     1711
Cendlineest_Lower_soil_sampling_depth_cm_centred    -0.01      0.03    -0.07     0.04 1.04      661     2839
Yieldendlineesttha_Tillage_catNT                  -1.18      0.80    -2.77     0.38 1.01    21294    23227
Yieldendlineesttha_Tillage_catRT                  -0.12      0.84    -1.77     1.55 1.01   186410    31070
Yieldendlineesttha_Cover_crop_proportion            0.04      1.09    -2.08     2.21 1.01     3449    14350
Yieldendlineesttha_Ley_duration                   -0.16      0.37    -0.94     0.54 1.04      634     1858
Yieldendlineesttha_Study_duration_centred          -0.03      0.04    -0.10     0.05 1.01     3683    38450
Yieldendlineesttha_Latitude_centred                0.10      0.33    -0.57     0.74 1.01     2887    71097
Yieldendlineesttha_Yield_endline_cropDurumwheat     -4.87      4.99   -14.36     5.48 1.00    48900    77226
Yieldendlineesttha_Yield_endline_cropMaize          8.66      3.31     2.16    15.46 1.00    60013    76163
Yieldendlineesttha_Yield_endline_cropSpringbarley    -5.08      3.09   -11.13     1.25 1.00    53641    71841
Yieldendlineesttha_Yield_endline_cropWheat         -5.87      5.86   -17.29     5.89 1.01     4799    67704
Yieldendlineesttha_Yield_endline_cropWinterbarley    -1.92      5.07   -12.48     7.77 1.01    21233    45350
Yieldendlineesttha_Yield_endline_cropWinterwheat    -4.04      3.21   -10.38     2.42 1.00    53808    70996

Family Specific Parameters:
                          Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest             0.08      0.01     0.05     0.10 1.48       74      320
sigma_Yieldendlineesttha      2.09      0.34     1.46     2.73 1.45       77      340

Residual Correlations:
                                        Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)      0.20      0.13    -0.06     0.43 1.01     5179    98468

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

4. EIBI

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + C_baseline_est_centred + 
Clay_all_centred + Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID) 
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Yield_endline_crop + (1 | a | 
Unique_study_ID) 
   Data: NTCCLA_SOC_yield_ErrorBase_IMPUTED (Number of observations: 195) 
  Draws: 40 chains, each with iter = 8000; warmup = 4000; thin = 1;
         total post-warmup draws = 160000

Group-Level Effects: 
~Unique_study_ID (Number of levels: 40) 
                                                       Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                                  0.84      0.12     0.64     1.10 1.06      364     1299
sd(Yieldendlineesttha_Intercept)                          11.49      1.57     8.87    15.01 1.00    74578   109260
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)     0.17      0.19    -0.22     0.52 1.00    13514   105112

Population-Level Effects: 
                                                                  Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                                                 1.73      0.14     1.46     2.00 1.02     1473     3872
Yieldendlineesttha_Intercept                                         12.62      3.32     6.01    19.09 1.00    82663   103438
Cendlineest_Tillage_catNT                                             0.06      0.03     0.00     0.11 1.01     2173    11491
Cendlineest_Tillage_catRT                                             0.09      0.03     0.03     0.14 1.03      867     3927
Cendlineest_Cover_crop_proportion                                     0.07      0.04    -0.01     0.15 1.11      219      459
Cendlineest_Ley_duration                                              0.05      0.01     0.03     0.08 1.03      713     3402
Cendlineest_Study_duration_centred                                    0.00      0.00    -0.00     0.00 1.09      261     1403
Cendlineest_Latitude_centred                                          0.04      0.04    -0.04     0.12 1.02     1221     9255
Cendlineest_C_baseline_est_centred                                    0.06      0.08    -0.10     0.19 2.10       52      210
Cendlineest_Clay_all_centred                                         -0.03      0.02    -0.07     0.00 1.06      361     1058
Cendlineest_Lower_soil_sampling_depth_cm_centred                     -0.05      0.02    -0.09    -0.02 1.01     1941    10290
Yieldendlineesttha_Tillage_catNT                                     -0.86      0.78    -2.39     0.66 1.00   267808   132189
Yieldendlineesttha_Tillage_catRT                                     -0.46      0.75    -1.94     1.02 1.00   259395   131205
Yieldendlineesttha_Cover_crop_proportion                              0.09      0.99    -1.84     2.04 1.00   261505   127355
Yieldendlineesttha_Ley_duration                                       0.19      0.29    -0.38     0.77 1.00   277442   118330
Yieldendlineesttha_Study_duration_centred                            -0.05      0.05    -0.16     0.06 1.00   240784   122237
Yieldendlineesttha_Latitude_centred                                   0.35      0.62    -0.88     1.59 1.00    91365   104311
Yieldendlineesttha_Yield_endline_cropAveragedMgrainequivalentkgDha    -7.30     12.09   -30.93    16.75 1.00   199933   119981
Yieldendlineesttha_Yield_endline_cropBarley                          -3.21      3.11    -9.35     2.86 1.01     4102   118051
Yieldendlineesttha_Yield_endline_cropDurumwheat                      -7.35     12.52   -31.90    17.43 1.00   177389   120807
Yieldendlineesttha_Yield_endline_cropMaize                            2.74      5.85    -8.57    14.43 1.00   101350   109238
Yieldendlineesttha_Yield_endline_cropMix:springwheatMfababean       -10.88      7.20   -24.87     3.42 1.00    93085   108376
Yieldendlineesttha_Yield_endline_cropSpringbarley                    -4.35      2.93   -10.13     1.37 1.00   138698   123624
Yieldendlineesttha_Yield_endline_cropSpringoats                     -14.94     11.36   -37.16     7.67 1.00   112906   114871
Yieldendlineesttha_Yield_endline_cropSpringwheat                     -9.61      6.74   -22.68     3.90 1.00    89322   102734
Yieldendlineesttha_Yield_endline_cropSugarbeet                       76.90      7.27    62.71    91.34 1.00    94134   107317
Yieldendlineesttha_Yield_endline_cropTriticale                       -9.41     11.80   -32.43    14.05 1.00   209861   120296
Yieldendlineesttha_Yield_endline_cropWheat                           -6.48     10.59   -27.17    14.60 1.00   126947   119585
Yieldendlineesttha_Yield_endline_cropWinterbarley                   -11.96      9.89   -31.33     7.74 1.00   128364   115374
Yieldendlineesttha_Yield_endline_cropWinterwheat                     -2.97      2.44    -7.79     1.80 1.00   141198   121621

Family Specific Parameters: 
                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest            0.10      0.01     0.08     0.12 1.43       79      303
sigma_Yieldendlineesttha     2.99      0.20     2.63     3.40 1.00   118166   119651

Residual Correlations: 
                                       Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)     0.12      0.09    -0.07     0.30 1.12      196      699

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
```

scale reduction factor on split chains (at convergence, Rhat = 1).

Note that indicators of non-convergence (Rhat > 1.05) are taken here as false-positives and reflect non-convergence between models fitted to each of the 10 imputed datasets rather than non-convergence within models

5a. Sensitivity analysis: critical appraisal

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + C_baseline_est_centred + Clay_all_centred + Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID)
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Study_duration_centred + Latitude_centred + Yield_endline_crop + (1 | a | Unique_study_ID)
   Data: NTCCLA_SOC_yield_ErrorBase_CA_IMPUTED (Number of observations: 152)
  Draws: 40 chains, each with iter = 8000; warmup = 4000; thin = 1;
         total post-warmup draws = 160000

Group-Level Effects:
~Unique_study_ID (Number of levels: 26)
                                                     Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                                0.61      0.11     0.45     0.85 1.01     2617    84441
sd(Yieldendlineesttha_Intercept)                         3.26      0.69     2.19     4.87 1.00    75923   100448
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)  -0.37     0.26    -0.78     0.22 1.01     9443   100885

Population-Level Effects:
                                                          Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                                         1.47      0.12     1.22     1.71 1.00    44159    74077
Yieldendlineesttha_Intercept                                  6.70      1.50     3.64     9.57 1.00    71088    91824
Cendlineest_Tillage_catNT                                     0.04      0.03    -0.01     0.10 1.03      732     3369
Cendlineest_Tillage_catRT                                     0.04      0.03    -0.01     0.09 1.03      712     2544
Cendlineest_Cover_crop_proportion                             0.06      0.03    -0.00     0.12 1.05      466     2153
Cendlineest_Ley_duration                                      0.05      0.01     0.03     0.07 1.01     2892    12255
Cendlineest_Study_duration_centred                            0.00      0.00    -0.00     0.00 1.09      253      614
Cendlineest_Latitude_centred                                  0.02      0.04    -0.07     0.10 1.08      299     1402
Cendlineest_C_baseline_est_centred                            0.13      0.12    -0.04     0.42 1.61       66      162
Cendlineest_Clay_all_centred                                 -0.03      0.02    -0.07     0.01 1.08      280     1179
Cendlineest_Lower_soil_sampling_depth_cm_centred             -0.07      0.02    -0.10    -0.03 1.01     2069    12718
Yieldendlineesttha_Tillage_catNT                             -0.76      0.51    -1.76     0.24 1.00   251931   132456
Yieldendlineesttha_Tillage_catRT                             -0.26      0.48    -1.21     0.69 1.00   253290   133022
Yieldendlineesttha_Cover_crop_proportion                      0.23      0.63    -1.00     1.45 1.00   248195   125131
Yieldendlineesttha_Ley_duration                               0.17      0.16    -0.14     0.49 1.00   259616   122359
Yieldendlineesttha_Study_duration_centred                    -0.03      0.03    -0.08     0.02 1.00   213753   125979
Yieldendlineesttha_Latitude_centred                           0.07      0.24    -0.41     0.53 1.00    92212   102081
Yieldendlineesttha_Yield_endline_cropAveragedMgrainequivalentkgDha   -2.40      3.38    -8.97     4.41 1.00   157069   117040
Yieldendlineesttha_Yield_endline_cropBarley                  -2.14      2.83    -7.65     3.57 1.00   101397   110170
Yieldendlineesttha_Yield_endline_cropDurumwheat              -1.99      3.81    -9.43     5.70 1.00   124485   114443
Yieldendlineesttha_Yield_endline_cropMaize                    7.78      2.40     3.13    12.61 1.00   103624   107222
Yieldendlineesttha_Yield_endline_cropMix:springwheatMfababean   -2.18      2.82    -7.68     3.42 1.00    76727   101559
Yieldendlineesttha_Yield_endline_cropSpringbarley            -2.83      1.46    -5.65     0.07 1.00   112055   118816
Yieldendlineesttha_Yield_endline_cropSpringwheat             -0.93      2.50    -5.79     4.07 1.00    68519    89860
Yieldendlineesttha_Yield_endline_cropSugarbeet               85.16      2.98    79.34    91.07 1.00    67332   104981
Yieldendlineesttha_Yield_endline_cropTriticale               -3.19      3.49   -10.01     3.79 1.00   138657   115552
Yieldendlineesttha_Yield_endline_cropWheat                   -3.59      5.00   -13.43     6.39 1.00   107822   111693
Yieldendlineesttha_Yield_endline_cropWinterbarley            -0.02      3.55    -6.74     7.31 1.00    45493    99741
Yieldendlineesttha_Yield_endline_cropWinterwheat             -1.46      1.22    -3.82     0.94 1.00   116460   120008

Family Specific Parameters:
                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest            0.08      0.01     0.06     0.10 1.31       96      283
sigma_Yieldendlineesttha     1.64      0.12     1.42     1.89 1.03      811     2314

Residual Correlations:
                                          Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)        0.10      0.09    -0.08     0.27 1.01     2397    68781

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

5b. Sensitivity analysis: study duration

```
Family: MV(gaussian, gaussian)
  Links: mu = identity; sigma = identity
         mu = identity; sigma = identity
Formula: C_endline_est | se(C_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Latitude_centred + C_baseline_est_centred + Clay_all_centred + Lower_soil_sampling_depth_cm_centred + (1 | a | Unique_study_ID)
         Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat + Cover_crop_proportion + Ley_duration + Latitude_centred + Yield_endline_crop + (1 | a | Unique_study_ID)
   Data: NTCCLA_SOC_yield_ErrorBase_SD_IMPUTED (Number of observations: 105)
  Draws: 40 chains, each with iter = 8000; warmup = 4000; thin = 1;
         total post-warmup draws = 160000

Group-Level Effects:
~Unique_study_ID (Number of levels: 23)
                                                     Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Cendlineest_Intercept)                                1.00      0.18     0.72     1.43 1.00    63771    97709
sd(Yieldendlineesttha_Intercept)                         3.79      0.73     2.67     5.49 1.00    68440    97680
cor(Cendlineest_Intercept,Yieldendlineesttha_Intercept)   0.15     0.28    -0.42     0.64 1.00    81280    95816
```

```
Population-Level Effects:
                                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Cendlineest_Intercept                        1.59      0.21     1.16     2.01 1.00    58748    81817
Yieldendlineesttha_Intercept                 8.48      1.10     6.30    10.65 1.00    81166   101346
Cendlineest_Tillage_catNT                    0.09      0.04     0.02     0.16 1.00   176778   132783
Cendlineest_Tillage_catRT                    0.09      0.03     0.03     0.16 1.00   208940   134837
Cendlineest_Cover_crop_proportion            0.06      0.05    -0.04     0.15 1.02     1496     8766
Cendlineest_Ley_duration                     0.07      0.01     0.04     0.10 1.02     1214    21622
Cendlineest_Latitude_centred                 0.09      0.06    -0.04     0.21 1.00    31378    99137
Cendlineest_C_baseline_est_centred          -0.01      0.06    -0.14     0.10 1.41       81      123
Cendlineest_Clay_all_centred                -0.01      0.03    -0.06     0.05 1.01     7342   101423
Cendlineest_Lower_soil_sampling_depth_cm_centred    -0.03      0.03    -0.08     0.03 1.00    71317   102333
Yieldendlineesttha_Tillage_catNT            -0.01      0.25    -0.52     0.47 1.00     6349   102544
Yieldendlineesttha_Tillage_catRT             0.13      0.26    -0.37     0.64 1.01     2119    11097
Yieldendlineesttha_Cover_crop_proportion     0.07      0.34    -0.62     0.74 1.02     1194     5377
Yieldendlineesttha_Ley_duration              0.24      0.10     0.04     0.43 1.03      885     2182
Yieldendlineesttha_Latitude_centred          0.20      0.31    -0.42     0.82 1.00    72287    92376
Yieldendlineesttha_Yield_endline_cropAveragedMgrainequivalentkgDha    -3.68      4.04   -11.69     4.38 1.00   155305   117066
Yieldendlineesttha_Yield_endline_cropBarley    -0.38      0.77    -1.90     1.12 1.01    12853    11540
Yieldendlineesttha_Yield_endline_cropSpringbarley    -1.43      0.76    -2.92     0.08 1.01   163653    88924
Yieldendlineesttha_Yield_endline_cropSpringoats    -6.91      4.78   -16.30     2.60 1.00    81520    99977
Yieldendlineesttha_Yield_endline_cropTriticale    -5.29      3.81   -12.84     2.30 1.00   178390   113483
Yieldendlineesttha_Yield_endline_cropWheat    -3.19      5.50   -14.14     7.66 1.00    98496   108660
Yieldendlineesttha_Yield_endline_cropWinterbarley    -5.22      4.45   -14.02     3.57 1.00   123754   113375
Yieldendlineesttha_Yield_endline_cropWinterwheat    -0.77      0.64    -2.04     0.49 1.01   149180    12983

Family Specific Parameters:
                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma_Cendlineest            0.09      0.01     0.07     0.11 1.01     2140    93916
sigma_Yieldendlineesttha     0.55      0.08     0.42     0.73 1.06      395     1278

Residual Correlations:
                                         Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
rescor(Cendlineest,Yieldendlineesttha)       0.35      0.11     0.12     0.55 1.01     3445   131557

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

6. Univariate analysis: SOC*intervention interaction

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est_t_ha | se(Yield_endline_error, sigma = TRUE) ~ Tillage_cat * C_endline_est + Cover_crop_proportion * C_endline_est + Ley_duration * C_endline_est + Yield_endline_crop + (1 | Unique_study_ID)
   Data: NTCCLA_SOC_yield_ErrorBase_IMPUTED (Number of observations: 195)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_study_ID (Number of levels: 40)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)    11.15      1.48     8.66    14.40 1.00    17028    25629

Population-Level Effects:
                                                Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                                           6.02      4.26    -2.44    14.28 1.00    18057    24256
Tillage_catNT                                      -0.94      1.67    -4.20     2.34 1.00    48258    31539
Tillage_catRT                                       0.44      1.51    -2.51     3.39 1.00    48553    33586
C_endline_est                                       4.22      2.03     0.26     8.22 1.00    30619    28657
Cover_crop_proportion                               0.22      3.28    -6.19     6.66 1.00    56009    30334
Ley_duration                                       -0.32      0.82    -1.93     1.27 1.00    50825    30190
Yield_endline_cropAveragedMgrainequivalentkgDha    -6.16     11.77   -28.96    17.31 1.00    46687    28074
Yield_endline_cropBarley                           -3.59      3.05    -9.63     2.34 1.00    29664    30433
Yield_endline_cropDurumwheat                       -6.37     11.94   -29.81    17.56 1.00    45068    28472
Yield_endline_cropMaize                             2.56      5.77    -8.74    14.05 1.00    18940    23715
Yield_endline_cropMix:springwheatMfababean        -10.48      7.03   -24.29     3.37 1.00    19257    25323
Yield_endline_cropSpringbarley                     -4.13      2.88    -9.80     1.48 1.00    29223    29692
Yield_endline_cropSpringoats                      -21.89     11.05   -43.54    -0.08 1.00    32571    27554
Yield_endline_cropSpringwheat                      -9.14      6.55   -21.87     3.87 1.00    18231    24049
Yield_endline_cropSugarbeet                        78.05      7.07    64.13    91.98 1.00    19068    25729
Yield_endline_cropTriticale                        -8.25     11.83   -31.52    15.43 1.00    44299    28415
Yield_endline_cropWheat                           -10.05      8.68   -26.96     7.10 1.00    32710    29418
Yield_endline_cropWinterbarley                    -16.19      9.52   -35.01     2.45 1.00    29746    28342
Yield_endline_cropWinterwheat                      -3.25      2.44    -8.05     1.50 1.00    26507    27851
Tillage_catNT:C_endline_est                        -0.13      0.92    -1.93     1.67 1.00    46314    32220
Tillage_catRT:C_endline_est                        -0.77      0.83    -2.39     0.85 1.00    43977    32059
C_endline_est:Cover_crop_proportion                -0.14      2.40    -4.82     4.55 1.00    56039    30343
C_endline_est:Ley_duration                          0.16      0.44    -0.70     1.03 1.00    52738    31103

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma     2.97      0.20     2.61     3.39 1.00    27671    28542

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
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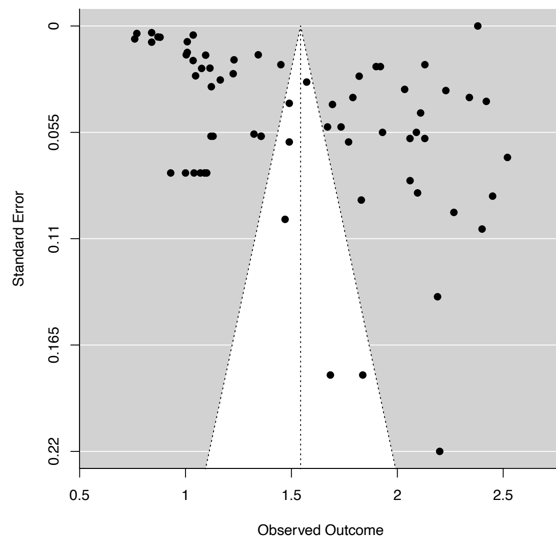
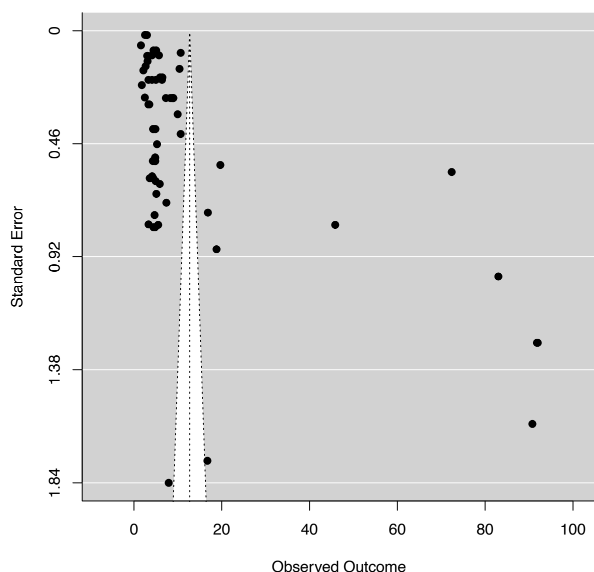
A2.2.3. Funnel plots

Endline SOC observations plotted against within-treatment standard errors, for EP dataset (see Methods in main text):



Results of regtest on rma: z= 3.4016, p=0.007

Endline Yield observations plotted against within-treatment standard errors, for EP dataset (see Methods in main text):



Results of regtest on rma: z= 5.4943, p= <0.0001

A2.2.4. SOC-yield relationship

<table>
<tr><td colspan="10">Table A2.8. Results of univariate analysis estimating the effect on ‘endline’ arable crop yield (t.ha^{-1}) of interactions between ‘endline’ soil organic carbon (g.100g^{-1}) and regenerative interventions, using EI (error imputed) dataset (195 observations from 40 studies). See Methods in main text for further details. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0</td></tr>
<tr><td rowspan="2">Intercept</td><td rowspan="2">SOC endline</td><td rowspan="2">No till</td><td rowspan="2">Reduced till</td><td rowspan="2">Cover crops</td><td rowspan="2">Ley-arable</td><td colspan="2">Standard deviation parameters</td><td colspan="2">R2</td></tr>
<tr><td>Within studies</td><td>Between studies</td><td>Whole model</td><td>Fixed effects</td></tr>
<tr><td>6.02 [-2.44, 14.3]</td><td>4.22 [0.26, 8.22]*</td><td>-0.94 [-4.20, 2.34]</td><td>0.44 [-2.51, 3.39]</td><td>0.22 [-6.19, 6.66]</td><td>-0.32 [-1.93, 1.27]</td><td rowspan="2">2.97 [2.61, 3.39]</td><td rowspan="2">11.15 [8.66, 14.40]</td><td rowspan="2">0.946</td><td rowspan="2">0.483</td></tr>
<tr><td colspan="2">SOC:intervention interaction terms</td><td>-0.13 [-1.93, 1.67]</td><td>-0.77 [-2.39, 0.85]</td><td>-0.14 [-4.82, 4.55]</td><td>0.16 [-0.70, 1.03]</td></tr>
</table>

A2.3. Additional Supplementary Figures

Figure A2.2. Forest plots showing treatment results from studies of reduced tillage intensity identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**)

cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text methods), these are presented in the confidence intervals. Tillage treatment categories are conventional tillage (CT), reduced tillage (RT) and no-till (NT). The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals for each tillage category from a tillage-only meta-analysis are also shown. Note that main analysis results presented in text were estimated using full dataset across all interventions (see Methods in main text for details).

Figure A2.3. Forest plots showing treatment results from studies of cover cropping identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**) cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text methods), these are presented in the confidence intervals. The proportion of years in the arable rotation that cover crops were present is given. The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals of cover crop presence in rotation for no years or all years (expressed as proportion) from a cover crop-only meta-analysis are also shown. Note that main analysis results presented in

text were estimated using full dataset across all interventions (see Methods in main text for details).

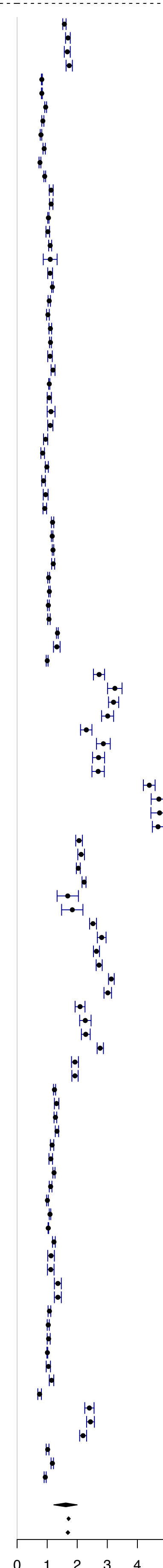
Figure A2.4. Forest plots showing treatment results from studies of ley-arable systems identified by systematic review, for (**a**) soil organic carbon (g.100g^{-1}) and (**b**) cash crop yield (t.ha^{-1}). Estimates of SOC and yield with 95% confidence intervals for each treatment extracted from studies are given in the table and plotted adjacent for each row. Where treatment standard errors were imputed for analysis (see main text methods), these are presented in the confidence intervals. The length of the ley phase within the arable rotation for each treatment is given in years. The number of soil samples (n) per treatment are given in (**a**), while the crop that yield was measured for are given in (**b**). Treatment duration at the point of SOC or yield measurement is given in years. Summary estimates and 95% credible intervals for ley durations of 0 and 1 year from a ley-arable-only meta-analysis are also shown. Note that main analysis results presented in text were estimated using full dataset across all interventions (see Methods in main text for details).

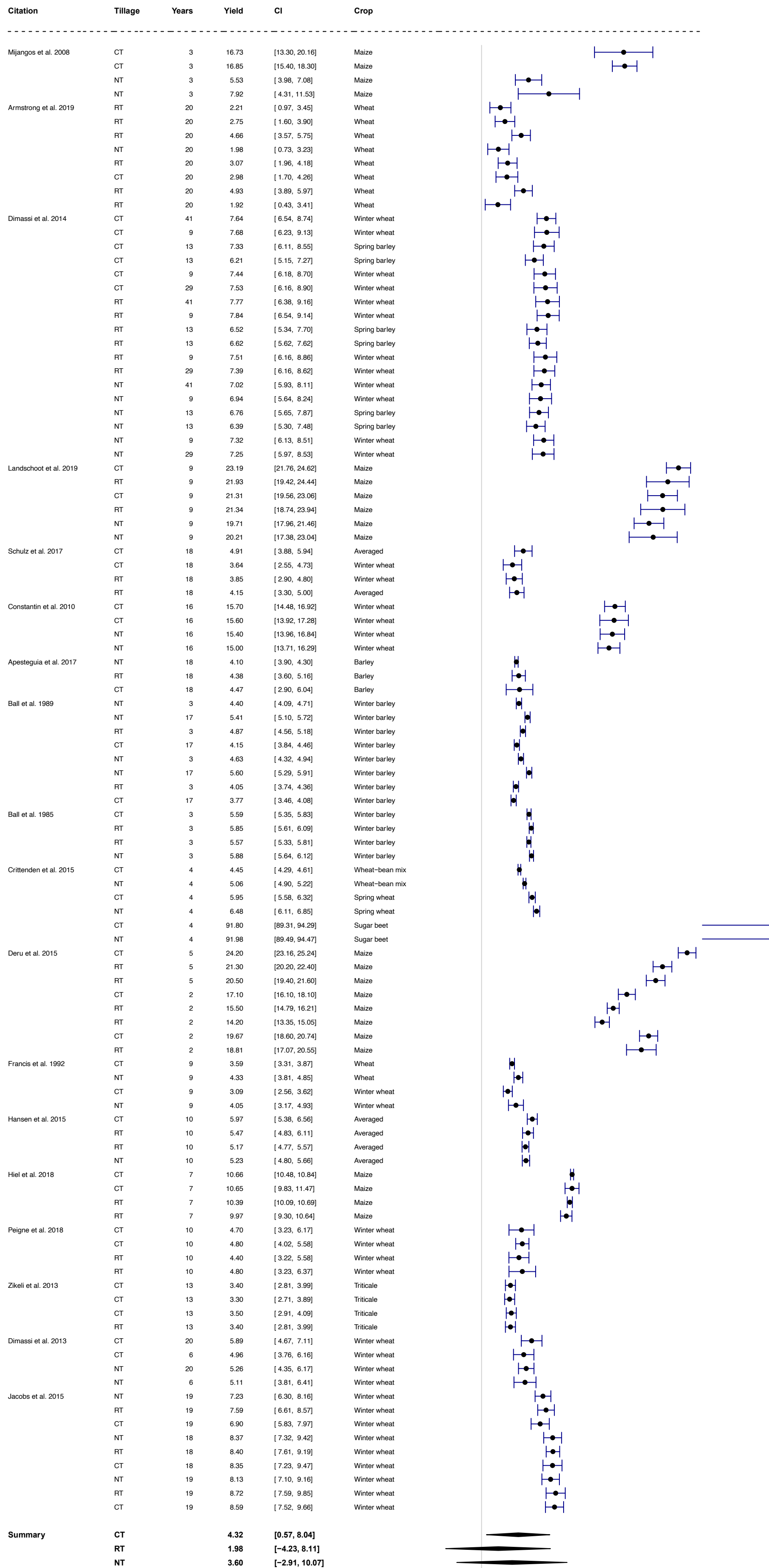
Figure A2.5. Effects of interventions on SOC concentration and crop yield. Conditional effects of (**a-b**) reducing tillage intensity, CT: conventional tillage, RT: reduced tillage, NT: no tillage, (**c-d**) cover cropping, proportion of years present in arable rotation, (**e-f**) ley-arable systems, 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% Predictive 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 A2.6. Effect sizes of practice predictor terms. Model effects from six meta-analytical models fitted to (**a**) soil organic carbon concentration (g.100g^{-1}) and (**b**) crop yield (t.ha^{-1}) data, with error bars showing 95% Credible Intervals, as presented in Table 3.2. EP: error present; EI: error imputed; EIBP: baseline present, error imputed; EIBI: baseline and error imputed; CA: critical appraisal sensitivity analysis; SD: study duration sensitivity analysis; see main text Methods for further details.

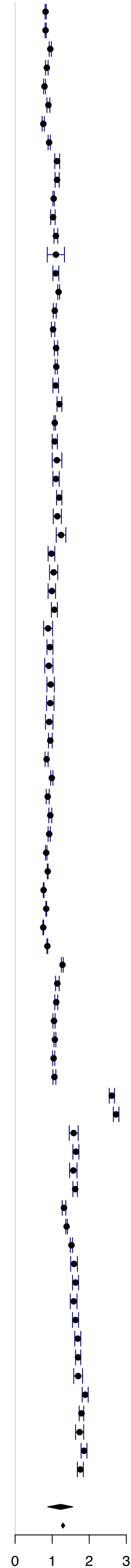
Citation	Tillage	Years	SOC	CI	n
Mijangos et al. 2008	CT	3	1.57	[1.52, 1.63]	3
	CT	3	1.69	[1.61, 1.77]	3
	NT	3	1.67	[1.57, 1.77]	3
	NT	3	1.73	[1.63, 1.84]	3
Armstrong et al. 2019	RT	20	0.82	[0.81, 0.84]	45
	RT	20	0.82	[0.81, 0.84]	45
	RT	20	0.95	[0.92, 0.98]	45
	NT	20	0.86	[0.82, 0.89]	45
	RT	20	0.79	[0.77, 0.82]	45
	CT	20	0.90	[0.86, 0.94]	45
	RT	20	0.76	[0.73, 0.79]	45
	RT	20	0.92	[0.89, 0.95]	45
Dimassi et al. 2014	CT	41	1.13	[1.07, 1.20]	16
	CT	9	1.13	[1.08, 1.19]	16
	CT	13	1.04	[1.02, 1.06]	16
	CT	13	1.02	[0.96, 1.08]	16
	CT	9	1.10	[1.05, 1.15]	16
	CT	29	1.10	[0.87, 1.33]	16
	RT	41	1.10	[1.02, 1.18]	16
	RT	9	1.17	[1.15, 1.20]	16
	RT	13	1.07	[1.03, 1.11]	16
	RT	13	1.02	[0.98, 1.07]	16
	RT	9	1.11	[1.06, 1.15]	16
	RT	29	1.11	[1.08, 1.14]	16
	NT	41	1.10	[1.02, 1.17]	16
	NT	9	1.20	[1.13, 1.26]	16
	NT	13	1.07	[1.05, 1.09]	16
	NT	13	1.07	[1.00, 1.14]	16
	NT	9	1.13	[1.00, 1.26]	16
	NT	29	1.10	[1.02, 1.19]	16
Landschoot et al. 2019	CT	9	0.95	[0.88, 1.02]	3
	RT	9	0.85	[0.79, 0.91]	3
	CT	9	0.99	[0.94, 1.04]	3
	RT	9	0.88	[0.82, 0.94]	3
	NT	9	0.95	[0.87, 1.03]	3
	NT	9	0.92	[0.86, 0.98]	3
Schulz et al. 2017	CT	18	1.18	[1.14, 1.22]	12
	CT	18	1.17	[1.14, 1.19]	12
	RT	18	1.19	[1.17, 1.22]	12
	RT	18	1.20	[1.15, 1.25]	12
Constantin et al. 2010	CT	16	1.05	[1.02, 1.08]	3
	CT	16	1.07	[1.05, 1.10]	3
	NT	16	1.04	[1.01, 1.07]	3
	NT	16	1.06	[1.02, 1.10]	3
Apesteguia et al. 2017	NT	18	1.34	[1.31, 1.37]	4
	RT	18	1.32	[1.21, 1.43]	4
	CT	18	1.00	[0.97, 1.03]	4
Ball et al. 1989	NT	3	2.73	[2.54, 2.91]	4
	NT	17	3.25	[3.01, 3.49]	4
	RT	3	3.21	[3.04, 3.38]	4
	CT	17	3.01	[2.81, 3.21]	4
	NT	3	2.30	[2.11, 2.49]	4
	NT	17	2.87	[2.64, 3.10]	4
	RT	3	2.71	[2.51, 2.91]	4
	CT	17	2.70	[2.49, 2.90]	4
Ball et al. 1985	CT	3	4.40	[4.20, 4.59]	4
	RT	3	4.72	[4.46, 4.97]	4
	RT	3	4.74	[4.45, 5.03]	4
	NT	3	4.69	[4.50, 4.87]	4
Crittenden et al. 2015	CT	4	2.06	[1.95, 2.17]	4
	NT	4	2.13	[2.02, 2.24]	4
	CT	4	2.03	[1.97, 2.10]	4
	NT	4	2.23	[2.16, 2.29]	4
	CT	4	1.68	[1.33, 2.04]	4
	NT	4	1.84	[1.48, 2.19]	4
Deru et al. 2015	CT	5	2.52	[2.41, 2.64]	4
	RT	5	2.81	[2.67, 2.96]	4
	RT	5	2.64	[2.54, 2.74]	4
	CT	2	2.73	[2.63, 2.83]	4
	RT	2	3.13	[3.04, 3.23]	4
	RT	2	3.02	[2.89, 3.14]	4
	CT	2	2.10	[1.93, 2.26]	4
	RT	2	2.27	[2.08, 2.46]	4
Francis et al. 1992	CT	9	2.28	[2.14, 2.43]	3
	NT	9	2.76	[2.66, 2.87]	3
	CT	9	1.93	[1.81, 2.04]	3
	NT	9	1.92	[1.82, 2.03]	3
Hansen et al. 2015	CT	10	1.24	[1.21, 1.28]	4
	RT	10	1.31	[1.24, 1.39]	4
	RT	10	1.28	[1.23, 1.32]	4
	NT	10	1.33	[1.27, 1.38]	4
Hiel et al. 2018	CT	7	1.16	[1.11, 1.22]	4
	CT	7	1.12	[1.06, 1.18]	4
	RT	7	1.23	[1.19, 1.26]	4
	RT	7	1.12	[1.07, 1.16]	4
Peigne et al. 2018	CT	10	1.01	[0.98, 1.04]	3
	CT	10	1.09	[1.07, 1.12]	3
	RT	10	1.04	[1.03, 1.05]	3
	RT	10	1.23	[1.18, 1.27]	3
Zikeli et al. 2013	CT	13	1.13	[1.02, 1.24]	8
	CT	13	1.12	[1.01, 1.23]	8
	CT	13	1.36	[1.24, 1.47]	8
	RT	13	1.36	[1.24, 1.47]	8
Dimassi et al. 2013	CT	20	1.08	[1.03, 1.12]	9
	CT	6	1.04	[1.00, 1.07]	9
	NT	20	1.05	[1.00, 1.10]	9
	NT	6	1.01	[0.99, 1.02]	9
Jacobs et al. 2015	NT	19	1.04	[0.97, 1.11]	30
	RT	19	1.15	[1.07, 1.22]	30
	CT	19	0.75	[0.69, 0.81]	30
	NT	18	2.40	[2.25, 2.56]	30
	RT	18	2.44	[2.31, 2.57]	30
	CT	18	2.19	[2.08, 2.31]	30
	NT	19	1.02	[0.97, 1.06]	30
	RT	19	1.17	[1.13, 1.21]	30
	CT	19	0.94	[0.90, 0.97]	30
Summary	**CT**		**1.62**	**[1.22, 2.00]**	**40**
	RT		**1.71**	**[1.66, 1.77]**	**36**
	NT		**1.69**	**[1.63, 1.75]**	**30**

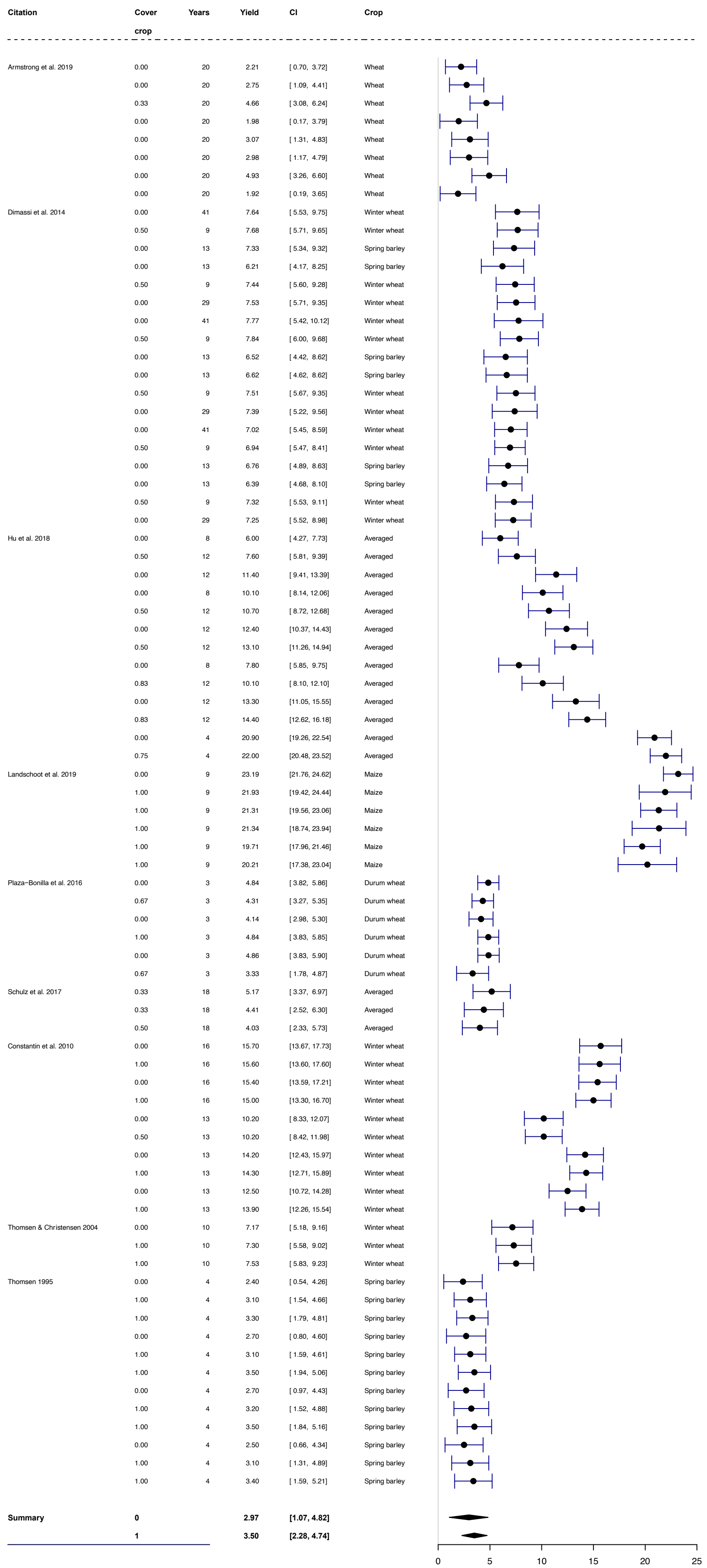




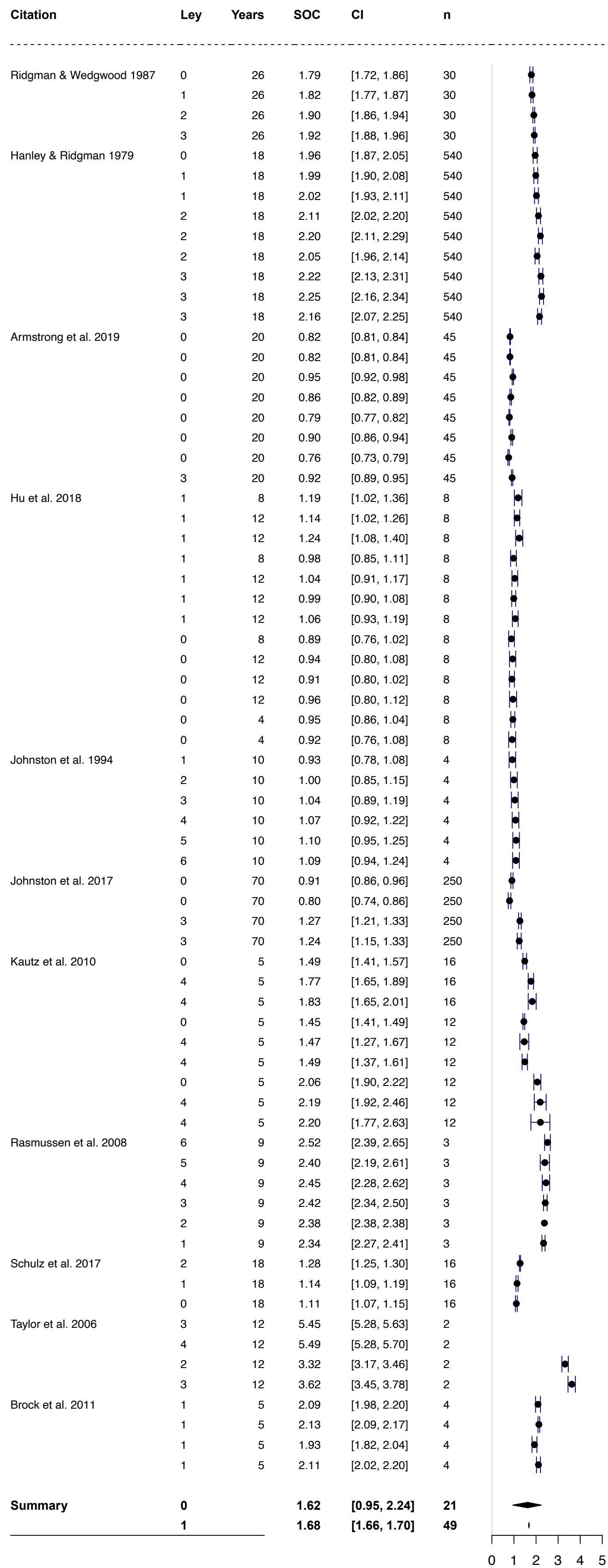
Citation Tillage Years Yield CI Crop
Mijangos et al. 2008 CT 3 16.73 [13.30, 20.16] Maize
CT 3 16.85 [15.40, 18.30] Maize
NT 3 5.53 [3.98, 7.08] Maize
NT 3 7.92 [4.31, 11.53] Maize
Armstrong et al. 2019 RT 20 2.21 [0.97, 3.45] Wheat
RT 20 2.75 [1.60, 3.90] Wheat
RT 20 4.66 [3.57, 5.75] Wheat
NT 20 1.98 [0.73, 3.23] Wheat
RT 20 3.07 [1.96, 4.18] Wheat
CT 20 2.98 [1.70, 4.26] Wheat
RT 20 4.93 [3.89, 5.97] Wheat
RT 20 1.92 [0.43, 3.41] Wheat
Dimassi et al. 2014 CT 41 7.64 [6.54, 8.74] Winter wheat
CT 9 7.68 [6.23, 9.13] Winter wheat
CT 13 7.33 [6.11, 8.55] Spring barley
CT 13 6.21 [5.15, 7.27] Spring barley
CT 9 7.44 [6.18, 8.70] Winter wheat
CT 29 7.53 [6.16, 8.90] Winter wheat
RT 41 7.77 [6.38, 9.16] Winter wheat
RT 9 7.84 [6.54, 9.14] Winter wheat
RT 13 6.52 [5.34, 7.70] Spring barley
RT 13 6.62 [5.62, 7.62] Spring barley
RT 9 7.51 [6.16, 8.86] Winter wheat
RT 29 7.39 [6.16, 8.62] Winter wheat
NT 41 7.02 [5.93, 8.11] Winter wheat
NT 9 6.94 [5.64, 8.24] Winter wheat
NT 13 6.76 [5.65, 7.87] Spring barley
NT 13 6.39 [5.30, 7.48] Spring barley
NT 9 7.32 [6.13, 8.51] Winter wheat
NT 29 7.25 [5.97, 8.53] Winter wheat
Landschoot et al. 2019 CT 9 23.19 [21.76, 24.62] Maize
RT 9 21.93 [19.42, 24.44] Maize
CT 9 21.31 [19.56, 23.06] Maize
RT 9 21.34 [18.74, 23.94] Maize
NT 9 19.71 [17.96, 21.46] Maize
NT 9 20.21 [17.38, 23.04] Maize
Schulz et al. 2017 CT 18 4.91 [3.88, 5.94] Averaged
CT 18 3.64 [2.55, 4.73] Winter wheat
RT 18 3.85 [2.90, 4.80] Winter wheat
RT 18 4.15 [3.30, 5.00] Averaged
Constantin et al. 2010 CT 16 15.70 [14.48, 16.92] Winter wheat
CT 16 15.60 [13.92, 17.28] Winter wheat
NT 16 15.40 [13.96, 16.84] Winter wheat
NT 16 15.00 [13.71, 16.29] Winter wheat
Apesteguia et al. 2017 NT 18 4.10 [3.90, 4.30] Barley
RT 18 4.38 [3.60, 5.16] Barley
CT 18 4.47 [2.90, 6.04] Barley
Ball et al. 1989 NT 3 4.40 [4.09, 4.71] Winter barley
NT 17 5.41 [5.10, 5.72] Winter barley
RT 3 4.87 [4.56, 5.18] Winter barley
CT 17 4.15 [3.84, 4.46] Winter barley
NT 3 4.63 [4.32, 4.94] Winter barley
NT 17 5.60 [5.29, 5.91] Winter barley
RT 3 4.05 [3.74, 4.36] Winter barley
CT 17 3.77 [3.46, 4.08] Winter barley
Ball et al. 1985 CT 3 5.59 [5.35, 5.83] Winter barley
RT 3 5.85 [5.61, 6.09] Winter barley
RT 3 5.57 [5.33, 5.81] Winter barley
NT 3 5.88 [5.64, 6.12] Winter barley
Crittenden et al. 2015 CT 4 4.45 [4.29, 4.61] Wheat−bean mix
NT 4 5.06 [4.90, 5.22] Wheat−bean mix
CT 4 5.95 [5.58, 6.32] Spring wheat
NT 4 6.48 [6.11, 6.85] Spring wheat
CT 4 91.80 [89.31, 94.29] Sugar beet
NT 4 91.98 [89.49, 94.47] Sugar beet
Deru et al. 2015 CT 5 24.20 [23.16, 25.24] Maize
RT 5 21.30 [20.20, 22.40] Maize
RT 5 20.50 [19.40, 21.60] Maize
CT 2 17.10 [16.10, 18.10] Maize
RT 2 15.50 [14.79, 16.21] Maize
RT 2 14.20 [13.35, 15.05] Maize
CT 2 19.67 [18.60, 20.74] Maize
RT 2 18.81 [17.07, 20.55] Maize
Francis et al. 1992 CT 9 3.59 [3.31, 3.87] Wheat
NT 9 4.33 [3.81, 4.85] Wheat
CT 9 3.09 [2.56, 3.62] Winter wheat
NT 9 4.05 [3.17, 4.93] Winter wheat
Hansen et al. 2015 CT 10 5.97 [5.38, 6.56] Averaged
RT 10 5.47 [4.83, 6.11] Averaged
RT 10 5.17 [4.77, 5.57] Averaged
NT 10 5.23 [4.80, 5.66] Averaged
Hiel et al. 2018 CT 7 10.66 [10.48, 10.84] Maize
CT 7 10.65 [9.83, 11.47] Maize
RT 7 10.39 [10.09, 10.69] Maize
RT 7 9.97 [9.30, 10.64] Maize
Peigne et al. 2018 CT 10 4.70 [3.23, 6.17] Winter wheat
CT 10 4.80 [4.02, 5.58] Winter wheat
RT 10 4.40 [3.22, 5.58] Winter wheat
RT 10 4.80 [3.23, 6.37] Winter wheat
Zikeli et al. 2013 CT 13 3.40 [2.81, 3.99] Triticale
CT 13 3.30 [2.71, 3.89] Triticale
CT 13 3.50 [2.91, 4.09] Triticale
RT 13 3.40 [2.81, 3.99] Triticale
Dimassi et al. 2013 CT 20 5.89 [4.67, 7.11] Winter wheat
CT 6 4.96 [3.76, 6.16] Winter wheat
NT 20 5.26 [4.35, 6.17] Winter wheat
NT 6 5.11 [3.81, 6.41] Winter wheat
Jacobs et al. 2015 NT 19 7.23 [6.30, 8.16] Winter wheat
RT 19 7.59 [6.61, 8.57] Winter wheat
CT 19 6.90 [5.83, 7.97] Winter wheat
NT 18 8.37 [7.32, 9.42] Winter wheat
RT 18 8.40 [7.61, 9.19] Winter wheat
CT 18 8.35 [7.23, 9.47] Winter wheat
NT 19 8.13 [7.10, 9.16] Winter wheat
RT 19 8.72 [7.59, 9.85] Winter wheat
CT 19 8.59 [7.52, 9.66] Winter wheat
Summary CT 4.32 [0.57, 8.04]
RT 1.98 [−4.23, 8.11]
NT 3.60 [−2.91, 10.07]
−5 0 5 10 15 20 25

Citation	Cover crop	Years	SOC	CI	n
Armstrong et al. 2019	0.00	20	0.82	[0.81, 0.84]	45
	0.00	20	0.82	[0.81, 0.84]	45
	0.33	20	0.95	[0.92, 0.98]	45
	0.00	20	0.86	[0.82, 0.89]	45
	0.00	20	0.79	[0.77, 0.82]	45
	0.00	20	0.90	[0.86, 0.94]	45
	0.00	20	0.76	[0.73, 0.79]	45
	0.00	20	0.92	[0.89, 0.95]	45
Dimassi et al. 2014	0.00	41	1.13	[1.07, 1.20]	16
	0.50	9	1.13	[1.08, 1.19]	16
	0.00	13	1.04	[1.02, 1.06]	16
	0.00	13	1.02	[0.96, 1.08]	16
	0.50	9	1.10	[1.05, 1.15]	16
	0.00	29	1.10	[0.87, 1.33]	16
	0.00	41	1.10	[1.02, 1.18]	16
	0.50	9	1.17	[1.15, 1.20]	16
	0.00	13	1.07	[1.03, 1.11]	16
	0.00	13	1.02	[0.98, 1.07]	16
	0.50	9	1.11	[1.06, 1.15]	16
	0.00	29	1.11	[1.08, 1.14]	16
	0.00	41	1.10	[1.02, 1.17]	16
	0.50	9	1.20	[1.13, 1.26]	16
	0.00	13	1.07	[1.05, 1.09]	16
	0.00	13	1.07	[1.00, 1.14]	16
	0.50	9	1.13	[1.00, 1.26]	16
	0.00	29	1.10	[1.02, 1.19]	16
Hu et al. 2018	0.00	8	1.19	[1.12, 1.26]	8
	0.50	12	1.14	[1.03, 1.25]	8
	0.00	12	1.24	[1.11, 1.37]	8
	0.00	8	0.98	[0.89, 1.07]	8
	0.50	12	1.04	[0.93, 1.15]	8
	0.00	12	0.99	[0.89, 1.09]	8
	0.50	12	1.06	[0.98, 1.14]	8
	0.00	8	0.89	[0.77, 1.01]	8
	0.83	12	0.94	[0.86, 1.02]	8
	0.00	12	0.91	[0.80, 1.02]	8
	0.83	12	0.96	[0.86, 1.06]	8
	0.00	4	0.95	[0.85, 1.05]	8
	0.75	4	0.92	[0.82, 1.02]	8
Landschoot et al. 2019	0.00	9	0.95	[0.90, 1.00]	3
	1.00	9	0.85	[0.81, 0.89]	3
	1.00	9	0.99	[0.96, 1.02]	3
	1.00	9	0.88	[0.84, 0.92]	3
	1.00	9	0.95	[0.91, 0.99]	3
	1.00	9	0.92	[0.89, 0.95]	3
Plaza−Bonilla et al. 2016	0.00	3	0.84	[0.82, 0.86]	60
	0.67	3	0.88	[0.87, 0.89]	60
	0.00	3	0.77	[0.76, 0.78]	60
	1.00	3	0.84	[0.83, 0.85]	60
	0.00	3	0.76	[0.75, 0.77]	60
	0.67	3	0.87	[0.86, 0.88]	60
Schulz et al. 2017	0.33	18	1.28	[1.25, 1.30]	16
	0.33	18	1.14	[1.09, 1.19]	16
	0.50	18	1.11	[1.07, 1.15]	16
Constantin et al. 2010	0.00	16	1.05	[1.02, 1.08]	3
	1.00	16	1.07	[1.05, 1.10]	3
	0.00	16	1.04	[1.01, 1.07]	3
	1.00	16	1.06	[1.02, 1.10]	3
	0.00	13	2.61	[2.54, 2.68]	3
	0.50	13	2.72	[2.65, 2.80]	3
	0.00	13	1.58	[1.46, 1.70]	3
	1.00	13	1.64	[1.56, 1.72]	3
	0.00	13	1.57	[1.47, 1.67]	3
	1.00	13	1.62	[1.56, 1.68]	3
Thomsen & Christensen 2004	0.00	10	1.32	[1.27, 1.37]	12
	1.00	10	1.39	[1.37, 1.41]	12
	1.00	10	1.52	[1.49, 1.55]	12
Thomsen 1995	0.00	4	1.59	[1.50, 1.68]	3
	1.00	4	1.63	[1.55, 1.71]	3
	1.00	4	1.58	[1.49, 1.67]	3
	0.00	4	1.63	[1.55, 1.71]	3
	1.00	4	1.69	[1.61, 1.77]	3
	1.00	4	1.70	[1.63, 1.77]	3
	0.00	4	1.70	[1.58, 1.82]	3
	1.00	4	1.89	[1.81, 1.97]	3
	1.00	4	1.79	[1.73, 1.85]	3
	0.00	4	1.74	[1.63, 1.85]	3
	1.00	4	1.86	[1.78, 1.94]	3
	1.00	4	1.76	[1.68, 1.84]	3
Summary	**0**		**1.23**	**[0.88, 1.56]**	**40**
	1		**1.29**	**[1.25, 1.34]**	**39**

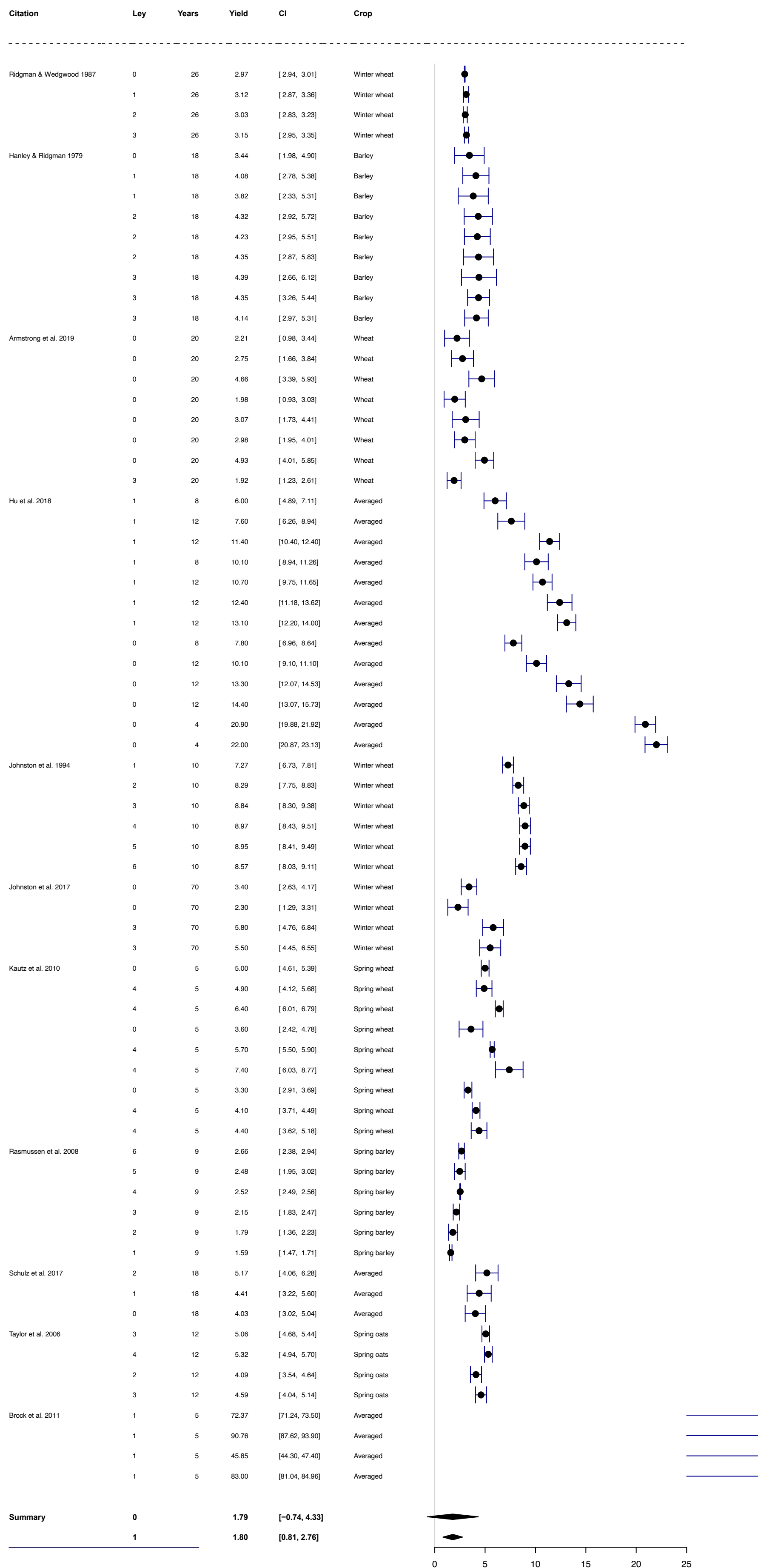




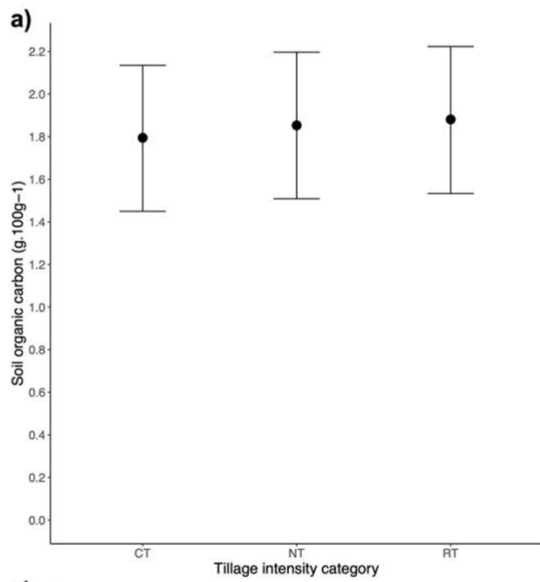
Citation
Cover crop
Years
Yield
CI
Crop
Armstrong et al. 2019 0.00 20 2.21 [0.70, 3.72] Wheat
0.00 20 2.75 [1.09, 4.41] Wheat
0.33 20 4.66 [3.08, 6.24] Wheat
0.00 20 1.98 [0.17, 3.79] Wheat
0.00 20 3.07 [1.31, 4.83] Wheat
0.00 20 2.98 [1.17, 4.79] Wheat
0.00 20 4.93 [3.26, 6.60] Wheat
0.00 20 1.92 [0.19, 3.65] Wheat
Dimassi et al. 2014 0.00 41 7.64 [5.53, 9.75] Winter wheat
0.50 9 7.68 [5.71, 9.65] Winter wheat
0.00 13 7.33 [5.34, 9.32] Spring barley
0.00 13 6.21 [4.17, 8.25] Spring barley
0.50 9 7.44 [5.60, 9.28] Winter wheat
0.00 29 7.53 [5.71, 9.35] Winter wheat
0.00 41 7.77 [5.42, 10.12] Winter wheat
0.50 9 7.84 [6.00, 9.68] Winter wheat
0.00 13 6.52 [4.42, 8.62] Spring barley
0.00 13 6.62 [4.62, 8.62] Spring barley
0.50 9 7.51 [5.67, 9.35] Winter wheat
0.00 29 7.39 [5.22, 9.56] Winter wheat
0.00 41 7.02 [5.45, 8.59] Winter wheat
0.50 9 6.94 [5.47, 8.41] Winter wheat
0.00 13 6.76 [4.89, 8.63] Spring barley
0.00 13 6.39 [4.68, 8.10] Spring barley
0.50 9 7.32 [5.53, 9.11] Winter wheat
0.00 29 7.25 [5.52, 8.98] Winter wheat
Hu et al. 2018 0.00 8 6.00 [4.27, 7.73] Averaged
0.50 12 7.60 [5.81, 9.39] Averaged
0.00 12 11.40 [9.41, 13.39] Averaged
0.00 8 10.10 [8.14, 12.06] Averaged
0.50 12 10.70 [8.72, 12.68] Averaged
0.00 12 12.40 [10.37, 14.43] Averaged
0.50 12 13.10 [11.26, 14.94] Averaged
0.00 8 7.80 [5.85, 9.75] Averaged
0.83 12 10.10 [8.10, 12.10] Averaged
0.00 12 13.30 [11.05, 15.55] Averaged
0.83 12 14.40 [12.62, 16.18] Averaged
0.00 4 20.90 [19.26, 22.54] Averaged
0.75 4 22.00 [20.48, 23.52] Averaged
Landschoot et al. 2019 0.00 9 23.19 [21.76, 24.62] Maize
1.00 9 21.93 [19.42, 24.44] Maize
1.00 9 21.31 [19.56, 23.06] Maize
1.00 9 21.34 [18.74, 23.94] Maize
1.00 9 19.71 [17.96, 21.46] Maize
1.00 9 20.21 [17.38, 23.04] Maize
Plaza−Bonilla et al. 2016 0.00 3 4.84 [3.82, 5.86] Durum wheat
0.67 3 4.31 [3.27, 5.35] Durum wheat
0.00 3 4.14 [2.98, 5.30] Durum wheat
1.00 3 4.84 [3.83, 5.85] Durum wheat
0.00 3 4.86 [3.83, 5.90] Durum wheat
0.67 3 3.33 [1.78, 4.87] Durum wheat
Schulz et al. 2017 0.33 18 5.17 [3.37, 6.97] Averaged
0.33 18 4.41 [2.52, 6.30] Averaged
0.50 18 4.03 [2.33, 5.73] Averaged
Constantin et al. 2010 0.00 16 15.70 [13.67, 17.73] Winter wheat
1.00 16 15.60 [13.60, 17.60] Winter wheat
0.00 16 15.40 [13.59, 17.21] Winter wheat
1.00 16 15.00 [13.30, 16.70] Winter wheat
0.00 13 10.20 [8.33, 12.07] Winter wheat
0.50 13 10.20 [8.42, 11.98] Winter wheat
0.00 13 14.20 [12.43, 15.97] Winter wheat
1.00 13 14.30 [12.71, 15.89] Winter wheat
0.00 13 12.50 [10.72, 14.28] Winter wheat
1.00 13 13.90 [12.26, 15.54] Winter wheat
Thomsen & Christensen 2004 0.00 10 7.17 [5.18, 9.16] Winter wheat
1.00 10 7.30 [5.58, 9.02] Winter wheat
1.00 10 7.53 [5.83, 9.23] Winter wheat
Thomsen 1995 0.00 4 2.40 [0.54, 4.26] Spring barley
1.00 4 3.10 [1.54, 4.66] Spring barley
1.00 4 3.30 [1.79, 4.81] Spring barley
0.00 4 2.70 [0.80, 4.60] Spring barley
1.00 4 3.10 [1.59, 4.61] Spring barley
1.00 4 3.50 [1.94, 5.06] Spring barley
0.00 4 2.70 [0.97, 4.43] Spring barley
1.00 4 3.20 [1.52, 4.88] Spring barley
1.00 4 3.50 [1.84, 5.16] Spring barley
0.00 4 2.50 [0.66, 4.34] Spring barley
1.00 4 3.10 [1.31, 4.89] Spring barley
1.00 4 3.40 [1.59, 5.21] Spring barley
Summary 0 2.97 [1.07, 4.82]
1 3.50 [2.28, 4.74]
0
5
10
15
20
25

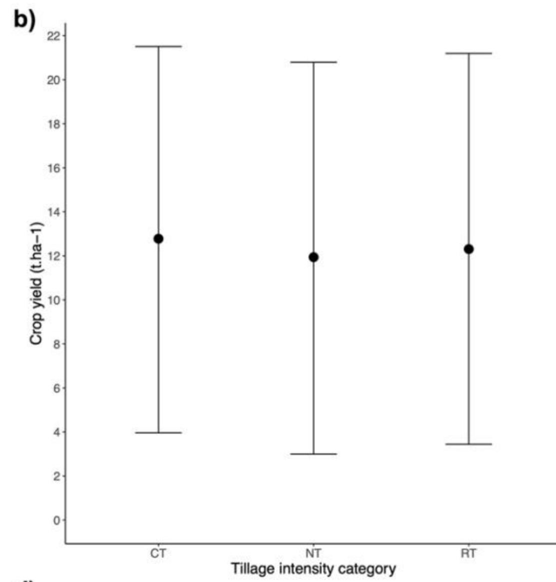


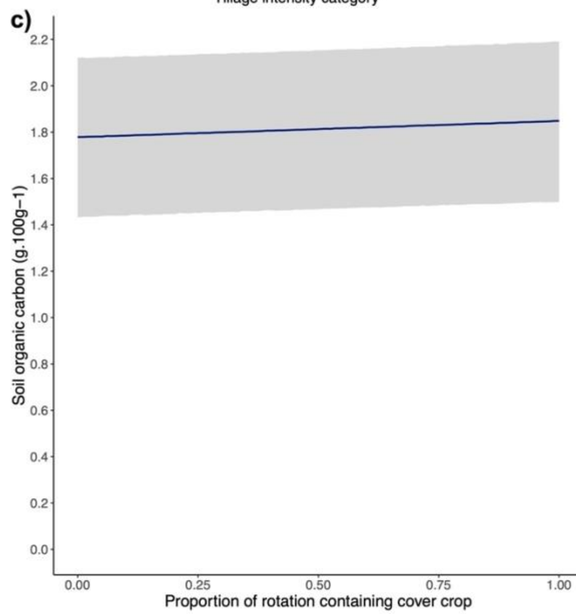
Citation	Ley	Years	SOC	CI	n
Ridgman & Wedgwood 1987	0	26	1.79	[1.72, 1.86]	30
	1	26	1.82	[1.77, 1.87]	30
	2	26	1.90	[1.86, 1.94]	30
	3	26	1.92	[1.88, 1.96]	30
Hanley & Ridgman 1979	0	18	1.96	[1.87, 2.05]	540
	1	18	1.99	[1.90, 2.08]	540
	1	18	2.02	[1.93, 2.11]	540
	2	18	2.11	[2.02, 2.20]	540
	2	18	2.20	[2.11, 2.29]	540
	2	18	2.05	[1.96, 2.14]	540
	3	18	2.22	[2.13, 2.31]	540
	3	18	2.25	[2.16, 2.34]	540
	3	18	2.16	[2.07, 2.25]	540
Armstrong et al. 2019	0	20	0.82	[0.81, 0.84]	45
	0	20	0.82	[0.81, 0.84]	45
	0	20	0.95	[0.92, 0.98]	45
	0	20	0.86	[0.82, 0.89]	45
	0	20	0.79	[0.77, 0.82]	45
	0	20	0.90	[0.86, 0.94]	45
	0	20	0.76	[0.73, 0.79]	45
	3	20	0.92	[0.89, 0.95]	45
Hu et al. 2018	1	8	1.19	[1.02, 1.36]	8
	1	12	1.14	[1.02, 1.26]	8
	1	12	1.24	[1.08, 1.40]	8
	1	8	0.98	[0.85, 1.11]	8
	1	12	1.04	[0.91, 1.17]	8
	1	12	0.99	[0.90, 1.08]	8
	1	12	1.06	[0.93, 1.19]	8
	0	8	0.89	[0.76, 1.02]	8
	0	12	0.94	[0.80, 1.08]	8
	0	12	0.91	[0.80, 1.02]	8
	0	12	0.96	[0.80, 1.12]	8
	0	4	0.95	[0.86, 1.04]	8
	0	4	0.92	[0.76, 1.08]	8
Johnston et al. 1994	1	10	0.93	[0.78, 1.08]	4
	2	10	1.00	[0.85, 1.15]	4
	3	10	1.04	[0.89, 1.19]	4
	4	10	1.07	[0.92, 1.22]	4
	5	10	1.10	[0.95, 1.25]	4
	6	10	1.09	[0.94, 1.24]	4
Johnston et al. 2017	0	70	0.91	[0.86, 0.96]	250
	0	70	0.80	[0.74, 0.86]	250
	3	70	1.27	[1.21, 1.33]	250
	3	70	1.24	[1.15, 1.33]	250
Kautz et al. 2010	0	5	1.49	[1.41, 1.57]	16
	4	5	1.77	[1.65, 1.89]	16
	4	5	1.83	[1.65, 2.01]	16
	0	5	1.45	[1.41, 1.49]	12
	4	5	1.47	[1.27, 1.67]	12
	4	5	1.49	[1.37, 1.61]	12
	0	5	2.06	[1.90, 2.22]	12
	4	5	2.19	[1.92, 2.46]	12
	4	5	2.20	[1.77, 2.63]	12
Rasmussen et al. 2008	6	9	2.52	[2.39, 2.65]	3
	5	9	2.40	[2.19, 2.61]	3
	4	9	2.45	[2.28, 2.62]	3
	3	9	2.42	[2.34, 2.50]	3
	2	9	2.38	[2.38, 2.38]	3
	1	9	2.34	[2.27, 2.41]	3
Schulz et al. 2017	2	18	1.28	[1.25, 1.30]	16
	1	18	1.14	[1.09, 1.19]	16
	0	18	1.11	[1.07, 1.15]	16
Taylor et al. 2006	3	12	5.45	[5.28, 5.63]	2
	4	12	5.49	[5.28, 5.70]	2
	2	12	3.32	[3.17, 3.46]	2
	3	12	3.62	[3.45, 3.78]	2
Brock et al. 2011	1	5	2.09	[1.98, 2.20]	4
	1	5	2.13	[2.09, 2.17]	4
	1	5	1.93	[1.82, 2.04]	4
	1	5	2.11	[2.02, 2.20]	4
Summary	**0**		**1.62**	**[0.95, 2.24]**	**21**
	1		**1.68**	**[1.66, 1.70]**	**49**

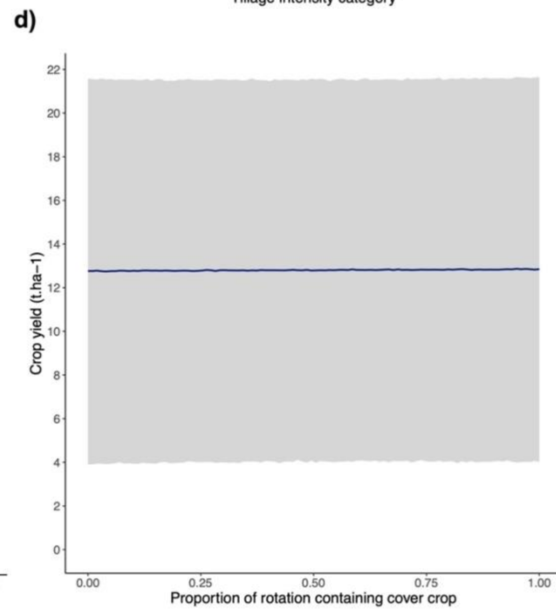


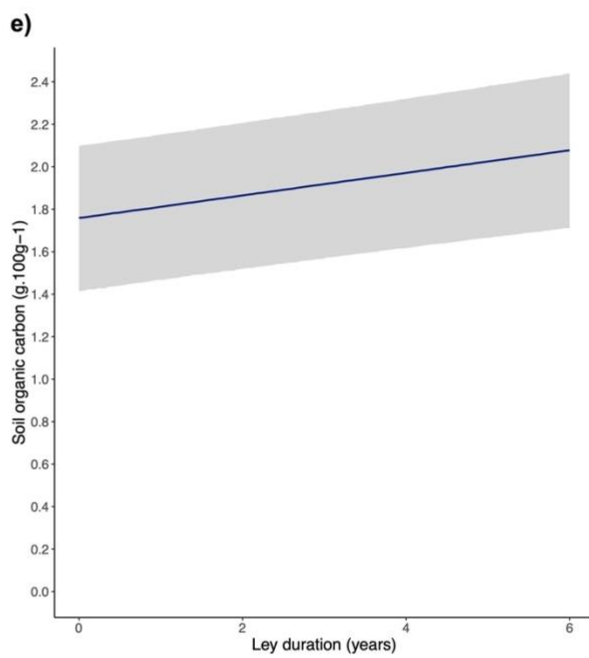
Citation	Ley	Years	Yield	CI	Crop
Ridgman & Wedgwood 1987	0	26	2.97	[2.94, 3.01]	Winter wheat
	1	26	3.12	[2.87, 3.36]	Winter wheat
	2	26	3.03	[2.83, 3.23]	Winter wheat
	3	26	3.15	[2.95, 3.35]	Winter wheat
Hanley & Ridgman 1979	0	18	3.44	[1.98, 4.90]	Barley
	1	18	4.08	[2.78, 5.38]	Barley
	1	18	3.82	[2.33, 5.31]	Barley
	2	18	4.32	[2.92, 5.72]	Barley
	2	18	4.23	[2.95, 5.51]	Barley
	2	18	4.35	[2.87, 5.83]	Barley
	3	18	4.39	[2.66, 6.12]	Barley
	3	18	4.35	[3.26, 5.44]	Barley
	3	18	4.14	[2.97, 5.31]	Barley
Armstrong et al. 2019	0	20	2.21	[0.98, 3.44]	Wheat
	0	20	2.75	[1.66, 3.84]	Wheat
	0	20	4.66	[3.39, 5.93]	Wheat
	0	20	1.98	[0.93, 3.03]	Wheat
	0	20	3.07	[1.73, 4.41]	Wheat
	0	20	2.98	[1.95, 4.01]	Wheat
	0	20	4.93	[4.01, 5.85]	Wheat
	3	20	1.92	[1.23, 2.61]	Wheat
Hu et al. 2018	1	8	6.00	[4.89, 7.11]	Averaged
	1	12	7.60	[6.26, 8.94]	Averaged
	1	12	11.40	[10.40, 12.40]	Averaged
	1	8	10.10	[8.94, 11.26]	Averaged
	1	12	10.70	[9.75, 11.65]	Averaged
	1	12	12.40	[11.18, 13.62]	Averaged
	1	12	13.10	[12.20, 14.00]	Averaged
	0	8	7.80	[6.96, 8.64]	Averaged
	0	12	10.10	[9.10, 11.10]	Averaged
	0	12	13.30	[12.07, 14.53]	Averaged
	0	12	14.40	[13.07, 15.73]	Averaged
	0	4	20.90	[19.88, 21.92]	Averaged
	0	4	22.00	[20.87, 23.13]	Averaged
Johnston et al. 1994	1	10	7.27	[6.73, 7.81]	Winter wheat
	2	10	8.29	[7.75, 8.83]	Winter wheat
	3	10	8.84	[8.30, 9.38]	Winter wheat
	4	10	8.97	[8.43, 9.51]	Winter wheat
	5	10	8.95	[8.41, 9.49]	Winter wheat
	6	10	8.57	[8.03, 9.11]	Winter wheat
Johnston et al. 2017	0	70	3.40	[2.63, 4.17]	Winter wheat
	0	70	2.30	[1.29, 3.31]	Winter wheat
	3	70	5.80	[4.76, 6.84]	Winter wheat
	3	70	5.50	[4.45, 6.55]	Winter wheat
Kautz et al. 2010	0	5	5.00	[4.61, 5.39]	Spring wheat
	4	5	4.90	[4.12, 5.68]	Spring wheat
	4	5	6.40	[6.01, 6.79]	Spring wheat
	0	5	3.60	[2.42, 4.78]	Spring wheat
	4	5	5.70	[5.50, 5.90]	Spring wheat
	4	5	7.40	[6.03, 8.77]	Spring wheat
	0	5	3.30	[2.91, 3.69]	Spring wheat
	4	5	4.10	[3.71, 4.49]	Spring wheat
	4	5	4.40	[3.62, 5.18]	Spring wheat
Rasmussen et al. 2008	6	9	2.66	[2.38, 2.94]	Spring barley
	5	9	2.48	[1.95, 3.02]	Spring barley
	4	9	2.52	[2.49, 2.56]	Spring barley
	3	9	2.15	[1.83, 2.47]	Spring barley
	2	9	1.79	[1.36, 2.23]	Spring barley
	1	9	1.59	[1.47, 1.71]	Spring barley
Schulz et al. 2017	2	18	5.17	[4.06, 6.28]	Averaged
	1	18	4.41	[3.22, 5.60]	Averaged
	0	18	4.03	[3.02, 5.04]	Averaged
Taylor et al. 2006	3	12	5.06	[4.68, 5.44]	Spring oats
	4	12	5.32	[4.94, 5.70]	Spring oats
	2	12	4.09	[3.54, 4.64]	Spring oats
	3	12	4.59	[4.04, 5.14]	Spring oats
Brock et al. 2011	1	5	72.37	[71.24, 73.50]	Averaged
	1	5	90.76	[87.62, 93.90]	Averaged
	1	5	45.85	[44.30, 47.40]	Averaged
	1	5	83.00	[81.04, 84.96]	Averaged
Summary	**0**		**1.79**	**[−0.74, 4.33]**	
	1		**1.80**	**[0.81, 2.76]**	


a)
Soil organic carbon (g.100g−1)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CT
NT
RT
Tillage intensity category


b)
Crop yield (t.ha−1)
22
20
18
16
14
12
10
8
6
4
2
0
CT
NT
RT
Tillage intensity category


c)
Soil organic carbon (g.100g−1)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
Proportion of rotation containing cover crop


d)
Crop yield (t.ha−1)
22
20
18
16
14
12
10
8
6
4
2
0
0.00
0.25
0.50
0.75
1.00
Proportion of rotation containing cover crop


e)
Soil organic carbon (g.100g−1)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
Ley duration (years)

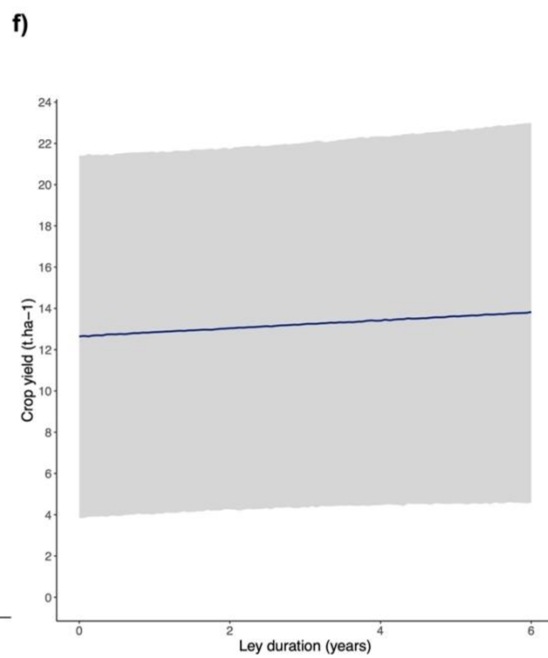

f)
Crop yield (t.ha−1)
24
22
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
Ley duration (years)

Figure A2.6a:

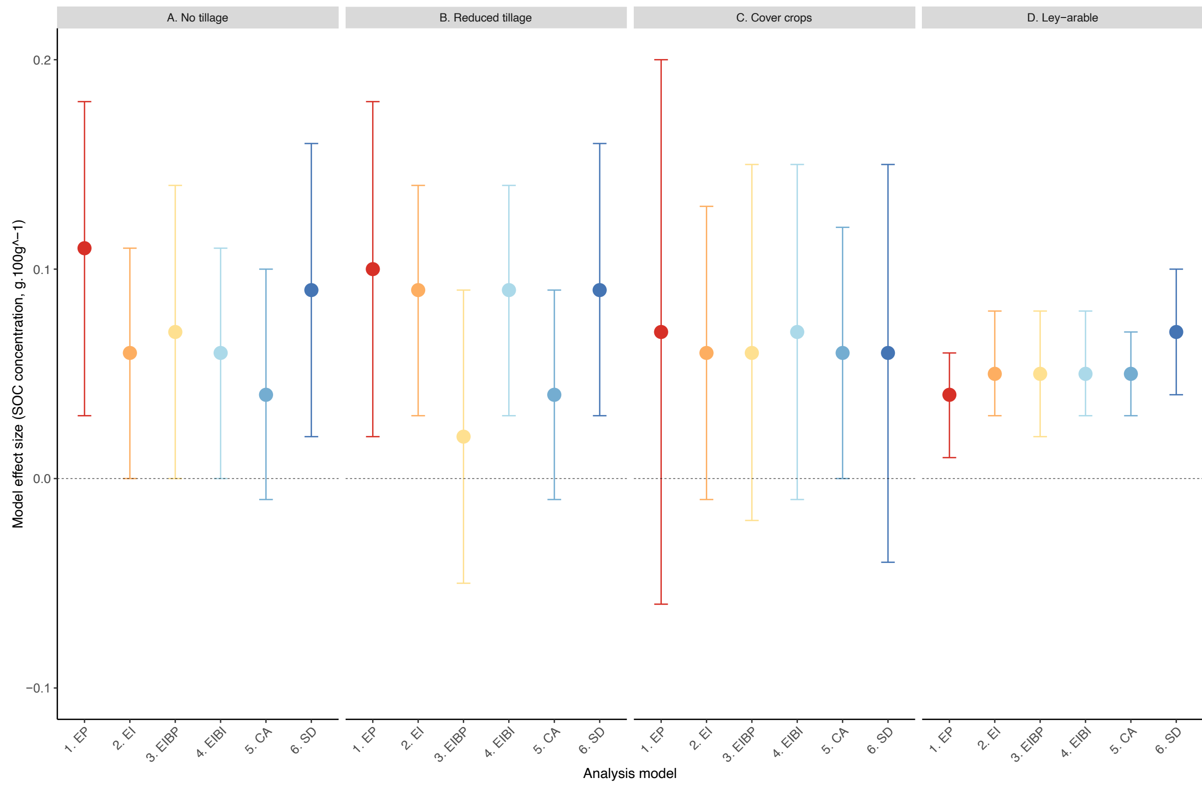
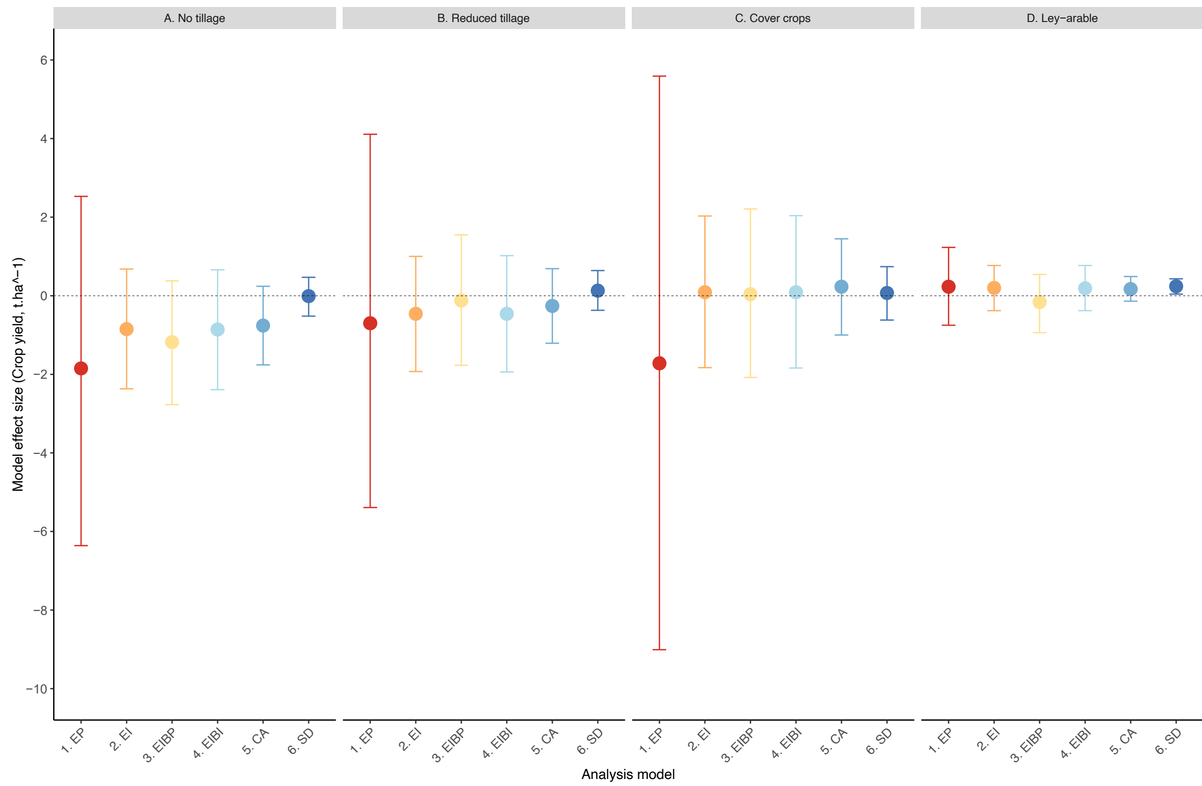


Figure A2.6b:



A2.4. References

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HADDAWAY, N. R., HEDLUND, K., JACKSON, L. E., KATTERER, T., LUGATO, E., THOMSEN, I. K., JORGENSEN, H. B. & SODERSTROM, B. 2015. What are the effects of agricultural management on soil organic carbon in boreo-temperate systems? *Environmental Evidence,* 4.

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Appendix 3. Supplementary Materials for Chapter 5

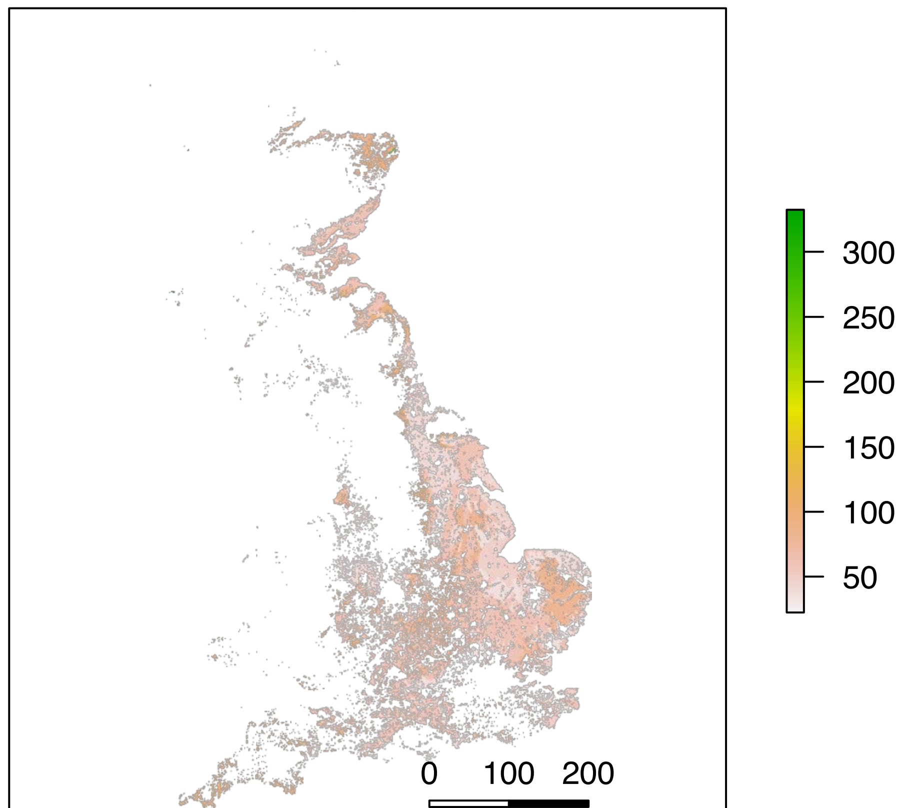
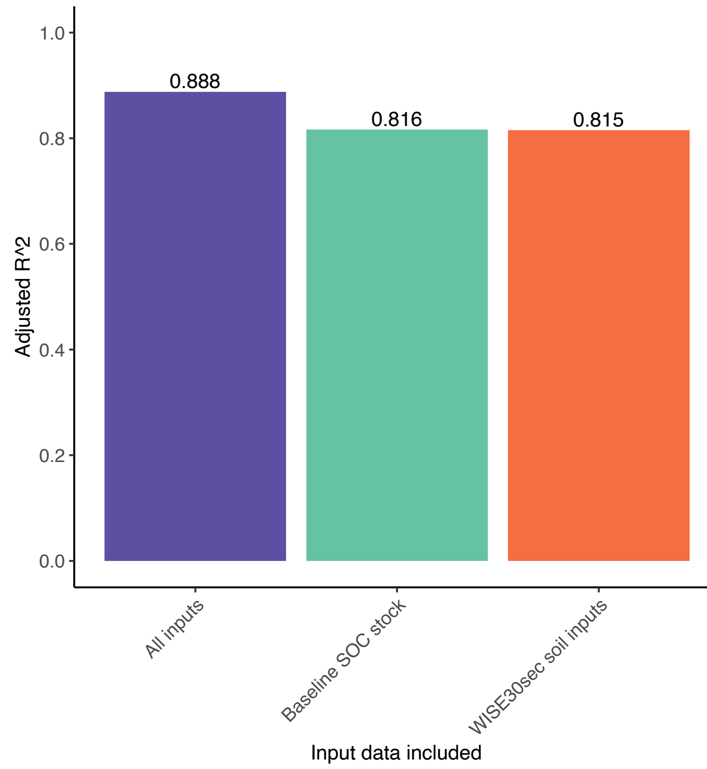


Figure A3.1. Baseline Great Britain arable soil organic carbon (SOC) stocks (t.ha^{-1}) at 1 km^2 resolution. Averaged across simulations for each intervention for 0-30 cm. Calculated from SOC concentration (g.100g-1) and bulk density data from the WISE30sec dataset (Batjes, 2016), for all GB arable land at 1 km^2 resolution identified through the CEH land cover map (Rowland et al., 2017). Scale bar in km.

a)



b)

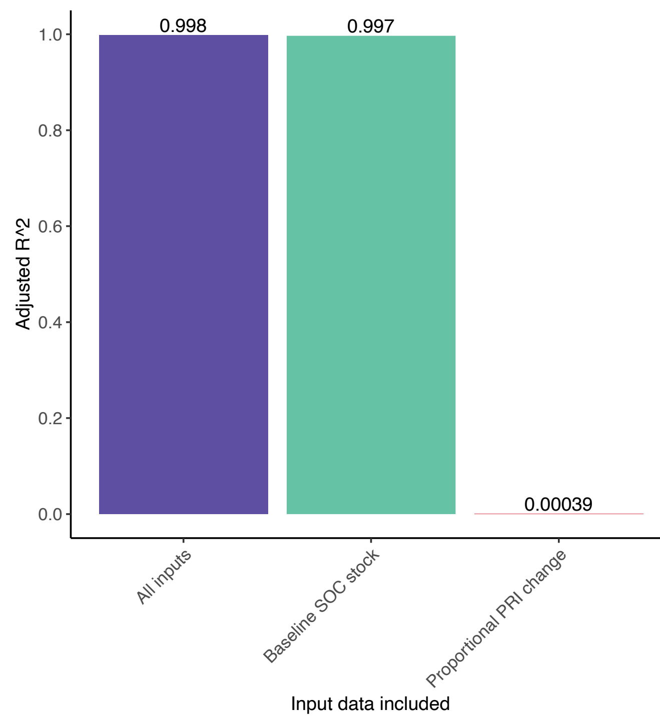
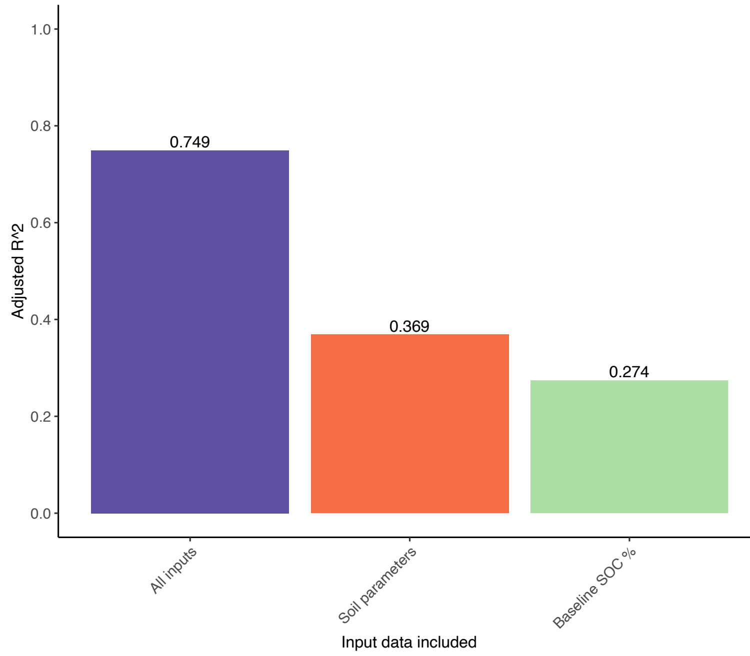


Figure A3.2. Proportion of uncertainty in RothC model output for Great Britain simulation explained by input parameter variation. Estimated from 6,137,400 observations (61,374 1 km^2 pixels) from the cover crop simulation. Adjusted R^2 from linear model with (**a**) baseline Plant Residue Input, and (**b**) soil carbon stock after 30 years of intervention, as response variables, and specified input parameter distributions as explanatory variables.

a)



b)

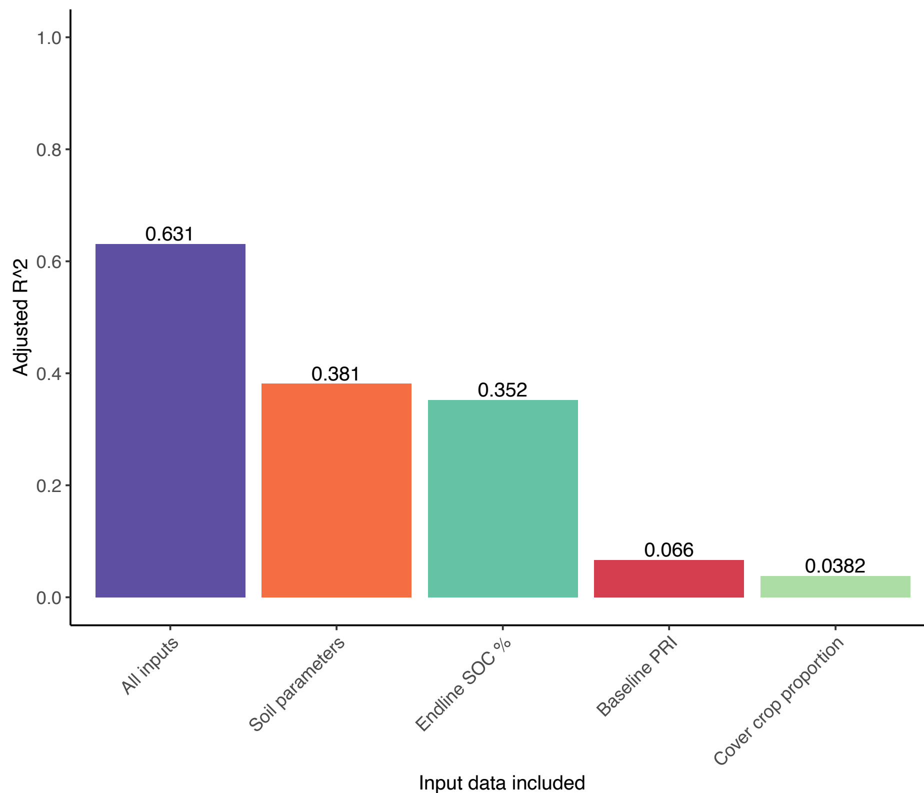


Figure A3.3. Proportion of uncertainty in RothC model output for model calibration explained by input parameter variation. Estimated using 61 observations from 8 studies with cover crop treatments identified by Jordon et al. (2021), i.e. CA data (see Table 5.2 and Section 5.4.1 for details). Adjusted R^2 from linear model with (**a**) treatment baseline Plant Residue Input, and (**b**) treatment endline Plant Residue Input, as response variables, and specified input parameter distributions as explanatory variables.

Appendix 4. Supplementary Materials for Chapter 6

A4.1. Systematic review methods

We used the Reporting standards for Systematic Evidence Syntheses to prepare these Supplementary Materials (Haddaway et al., 2017c) and developed and followed a predetermined protocol when conducting our review (unpublished). Below, we detail our literature searching and screening of records by title, abstract and full text, followed by reverse snowballing using citations in relevant reviews and primary research articles. We provide information on data extraction from relevant studies and critical appraisal, and further details of using these data for quantitative Bayesian meta-analysis. Further supporting files are provided online in the Zenodo repository (Jordon, 2022).

Table A4.1. Review question elements separated by Population, Intervention, Comparator, Outcome and Location (PICOL) for each intervention of interest

PICOL element	Rotational grazing (RG)	Herbal leys (HL)
Population	Pasture systems (including research stations, experimental plots, field trials and working farms but excluding greenhouse or laboratory experiments), typically grazed by sheep or cattle	
Intervention	Any grazing practice that includes a rest period for the pasture within the grazing season, i.e. livestock rotated between paddocks or fields allowing an ungrazed recovery period	Inclusion of a perennial forb in a pasture sward species composition, either in isolation or in combination with other forbs, grasses and/or clovers
Comparator	Continuous grazing (also known as set stocking), or rotational grazing with different grazing or rest periods to the Intervention	A sward with a different species composition, typically without or with a different perennial forb species to the Intervention
Outcomes	Soil organic carbon (SOC), soil organic matter (SOM) or soil total carbon (StC) where soils are shown to be free of carbonates, either as a concentration ($g.100g^{-1}$) or stock ($t.ha^{-1}$) Agricultural productivity: herbage dry matter yield ($t.ha^{-1}$), livestock daily liveweight gain ($g.day^{-1}$), milk yield ($kg.day^{-1}$), and sheep wool growth ($mg.cm^{-2}.day^{-1}$ or $g.day^{-1}$)	
Location	Regions with temperate oceanic climate with no dry season and warm summer (i.e. Köppen–Geiger climate classification Cfb (Peel et al., 2007)), restricted to countries that are exclusively Cfb (Britain including Ireland, Belgium, Netherlands, Luxembourg, New Zealand) or have substantial Cfb regions (France, Germany, Spain, Denmark, Australia).	

A4.1.1. Search strategy

We carried out the rotational grazing and herbal ley searches together due to the similarity between search terms (Table A4.2). Searches were conducted for "All years" in bibliographic databases and citation indices, with duplicate records automatically excluded in Endnote X9 before citation screening. We developed a test list of four articles (Braun et al., 2010, Orgill et al., 2018, Rutledge et al., 2017, Zaralis and Padel, 2017) to test the comprehensive of our search, which were all returned by our search string. We did not specifically search for grey literature and only included studies published in English in our database, but we are confident that this is unlikely to have biased our results as grey literature is unlikely to report sufficient data for inclusion in meta-analysis and most published literature in our geographic region of interest is in English, as found by Haddaway et al. (2017a). We did not include studies from other climatic zones to maximise the generalisability of our findings to the context of interest.

Table A4.2. Search strategy for systematic review

Search string	Appendix 4.1.1.2.

Bibliographic databases and citation indexes	Web of Science:
	• Web of Science Core Collection (1900–present)
	  ○ Science Citation Index Expanded (1900–present)
	  ○ Social Sciences Citation Index (1900–present)
	  ○ Arts & Humanities Citation Index (1975–present)
	  ○ Conference Proceedings Citation Index-Science (1990–present)
	  ○ Conference Proceedings Citation Index-Social Science & Humanities (1990–present)
	  ○ Book Citation Index–Science (2005–present)
	  ○ Book Citation Index–Social Sciences & Humanities (2005–present)
	  ○ Emerging Sources Citation Index (2015–present)
	  ○ Current Chemical Reactions (1986–present) (includes *Institut National de la Propriete Industrielle* structure data back to 1840)
	  ○ Index Chemicus (1993–present)
	• BIOSIS Citation Index (1969–present)
	• Current Contents Connect (1998–present)
	• Data Citation Index (1993–present)
	• Derwent Innovations Index (1993–present)
	• KCI-Korean Journal Database (1980–present)

	• MEDLINE® (1950–present) • Russian Science Citation Index (2005–present) • SciELO Citation Index (2002–present) • Zoological Record (1993–present) CAB Abstracts Scopus
Search date	22 Feb 2021
Search date range	All years
Grey literature searched	None
Languages searched	English
Snowballing from previous reviews and meta-analysis	Yes, see Appendix 4.1.1.1. Spreadsheet of iterative reverse snowballing process available online (Jordon, 2022).

A4.1.1.1. Snowballing

As part of our initial search strategy, we conducted title screening of the reference lists of relevant reviews and meta-analyses (Conant et al., 2017, Conant et al., 2001, Gosnell et al., 2019, Whitehead, 2020, Whitehead et al., 2018) to identify additional relevant citations through 'reverse snowballing'. However, our search and reverse snowballing of relevant reviews returned only three relevant articles on rotational grazing and six on herbal leys, of which three presented both SOC and productivity measurements, one presented only SOC data and five presented only productivity data. This was at least in part because our search terms were designed to return studies that contained both soil carbon *and* productivity data, to enable a paired analysis similar to Jordon et al. (2022). Amending the search to intentionally capture studies that measured only one of soil carbon *or* productivity returned 24,179 citations from Web of Science alone which was deemed unfeasible to screen with the resources available. Therefore, we instead conducted further reverse snowballing on relevant articles identified by our initial search and by successive iterations of snowballing, until no more relevant articles were identified. This resulted in a further 72 relevant articles, all containing productivity measurements only. Our iterative reverse snowballing process is summarised in Table A4.3, full citation

details are provided in a spreadsheet online (Jordon, 2022), and the overall search and screening process is given in Fig A4.1.

Table A4.3. Summary of reverse snowballing process to identify further relevant records from reference lists of included articles.

Snowballing iteration	Total titles searched for	Full text not available	Abstract not relevant	Downloaded
1	13	0	0	13
2	32	5	0	27
3	38	5	4	29
4	48	7	18	23
5	33	9	17	7
6	10	2	2	6
7	5	3	2	0
Total	**179**	**31**	**43**	**105**

A4.1.1.2. Search string

<u>Web of Science</u>

TS=(soil*)

AND

TS=(agricult* OR farm* OR grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR fodder OR forage OR hay OR silage OR ruminant OR ruminants OR livestock OR stock OR stocking OR sheep OR ewe OR ewes OR lamb OR lambs OR "Ovis aries" OR ovine OR “Bos taurus” OR beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR bovine)

AND

TS=(“rotat* stock*” OR “mob stock*” OR “mob-stock*” OR “cell* stock*” OR “control* stock*” OR “paddock* stock*” OR “holistic* stock*” OR “plan* stock*” OR “manag* stock*” OR “strip* stock*” OR “adaptive* stock*” OR “precision stock*” OR

“regenerative stock*” OR “densit* stock*” OR “intens* stock*” OR “stock* intens*” OR “stock* densit*”

OR

“rotat* graz*” OR “mob-graz*” OR “mob graz*” OR “cell* graz*” OR “control* graz*” OR “paddock* graz*” OR “holistic* graz*” OR “plan* graz*” OR “manag* graz*” OR “strip* graz*” OR “adaptive* graz*” OR “precision graz*” OR “regenerative graz*” OR “densit* graz*” OR “intens* graz*” OR “graz* intens*” OR “graz* densit*”

OR

“multi*paddock” OR “grazing management” OR “grazing system” OR “grazing systems” OR “grazing technique” OR “pasture management” OR “regenerative agr*”

OR

ley* OR sward OR swards OR grass* OR ryegrass OR clover OR clovers OR “grass clover” OR legum* OR forb OR forbs OR herb OR herbs OR herbal OR herbage OR plantain OR chicory OR lucerne OR alfalfa OR sainfoin OR medic OR perennial*

OR

“fertility build*” OR multispecies OR “multi-species” OR “pasture composition” OR “sward composition” OR “species composition” OR “species diversity” OR “diverse mix*” OR “diverse sward*” OR “mixed sward*” OR “mixed ley*” OR “species mixture” OR “pasture species” OR “grassland species” OR “forage species” OR “deep* root*”)

AND

TS=(“soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM OR “carbon sequestrat*” OR “C sequestrat*”)

AND

TS=(yield* OR harvest* OR return* OR perform* OR productivity OR production OR biomass OR herbage OR forage OR “dry matter” OR DM OR “DM/ha” OR growth OR liveweight OR “live weight”)

AND

TS=(UK OR “United Kingdom” OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR France OR French OR Germany OR German OR Belgium OR Belgian OR Flemish OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR “New Zealand”)

<u>CAB Abstracts</u>

soil*

AND

agricult* OR farm* OR grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR fodder OR forage OR hay OR silage OR ruminant OR ruminants OR livestock OR stock OR stocking OR sheep OR ewe OR ewes OR lamb OR lambs OR Ovis aries OR ovine OR Bos taurus OR beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR bovine

AND

rotat* stock* OR mob stock* OR mob-stock* OR cell* stock* OR control* stock* OR paddock* stock* OR holistic* stock* OR plan* stock* OR manag* stock* OR strip* stock* OR adaptive* stock* OR precision stock* OR regenerative stock* OR densit* stock* OR intens* stock* OR stock* intens* OR stock* densit*

OR

rotat* graz* OR mob-graz* OR mob graz* OR cell* graz* OR control* graz* OR paddock* graz* OR holistic* graz* OR plan* graz* OR manag* graz* OR strip* graz* OR adaptive* graz* OR precision graz* OR regenerative graz* OR densit* graz* OR intens* graz* OR graz* intens* OR graz* densit*

OR

multi*paddock OR grazing management OR grazing system OR grazing systems OR grazing technique OR pasture management OR regenerative agr*

OR

ley* OR sward OR swards OR grass* OR ryegrass OR clover OR clovers OR grass clover OR legum* OR forb OR forbs OR herb OR herbs OR herbal OR herbage OR plantain OR chicory OR lucerne OR alfalfa OR sainfoin OR medic OR perennial*

OR

fertility build* OR multispecies OR multi-species OR pasture composition OR sward composition OR species composition OR species diversity OR diverse mix* OR diverse sward* OR mixed sward* OR mixed ley* OR species mixture OR pasture species OR grassland species OR forage species OR deep* root*

AND

soil organic carbon OR soil carbon OR soil C OR soil organic C OR SOC OR carbon pool OR carbon stock OR carbon storage OR soil organic matter OR SOM OR carbon sequestrat* OR C sequestrat*

AND

yield* OR harvest* OR return* OR perform* OR productivity OR production OR biomass OR herbage OR forage OR dry matter OR DM OR DM/ha OR growth OR liveweight OR live weight

AND

UK OR United Kingdom OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR France OR French OR Germany OR German OR Belgium OR Belgian OR Flemish OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR New Zealand

Scopus

TITLE-ABS-KEY(soil*)

AND

TITLE-ABS-KEY(agricult* OR farm* OR grazed OR grazing OR graze OR pasture OR pastures OR pastoral OR fodder OR forage OR hay OR silage OR ruminant OR ruminants OR livestock OR stock OR stocking OR sheep OR ewe OR ewes OR lamb OR lambs OR "Ovis aries" OR ovine OR “Bos taurus” OR beef OR dairy OR cattle OR cow OR bull OR steer OR heifer OR cows OR bulls OR steers OR heifers OR calf OR calves OR bovine)

AND

TITLE-ABS-KEY(“rotat* stock*” OR “mob stock*” OR “mob-stock*” OR “cell* stock*” OR “control* stock*” OR “paddock* stock*” OR “holistic* stock*” OR “plan* stock*” OR “manag* stock*” OR “strip* stock*” OR “adaptive* stock*” OR “precision stock*” OR “regenerative stock*” OR “densit* stock*” OR “intens* stock*” OR “stock* intens*” OR “stock* densit*”

OR

“rotat* graz*” OR “mob-graz*” OR “mob graz*” OR “cell* graz*” OR “control* graz*” OR “paddock* graz*” OR “holistic* graz*” OR “plan* graz*” OR “manag* graz*” OR

"strip* graz*" OR "adaptive* graz*" OR "precision graz*" OR "regenerative graz*" OR "densit* graz*" OR "intens* graz*" OR "graz* intens*" OR "graz* densit*"

OR

"multi*paddock" OR "grazing management" OR "grazing system" OR "grazing systems" OR "grazing technique" OR "pasture management" OR "regenerative agr*"

OR

ley* OR sward OR swards OR grass* OR ryegrass OR clover OR clovers OR "grass clover" OR legum* OR forb OR forbs OR herb OR herbs OR herbal OR herbage OR plantain OR chicory OR lucerne OR alfalfa OR sainfoin OR medic OR perennial*

OR

"fertility build*" OR multispecies OR "multi-species" OR "pasture composition" OR "sward composition" OR "species composition" OR "species diversity" OR "diverse mix*" OR "diverse sward*" OR "mixed sward*" OR "mixed ley*" OR "species mixture" OR "pasture species" OR "grassland species" OR "forage species" OR "deep* root*")

AND

TITLE-ABS-KEY("soil organic carbon" OR "soil carbon" OR "soil C" OR "soil organic C" OR SOC OR "carbon pool" OR "carbon stock" OR "carbon storage" OR "soil organic matter" OR SOM OR "carbon sequestrat*" OR "C sequestrat*")

AND

TITLE-ABS-KEY(yield* OR harvest* OR return* OR perform* OR productivity OR production OR biomass OR herbage OR forage OR "dry matter" OR DM OR "DM/ha" OR growth OR liveweight OR "live weight")

AND

TITLE-ABS-KEY(UK OR "United Kingdom" OR Britain OR British OR England OR English OR Scotland OR Scottish OR Wales OR Welsh OR Ireland OR Irish OR

France OR French OR Germany OR German OR Belgium OR Belgian OR Flemish OR Luxembourg OR Netherlands OR Holland OR Dutch OR Denmark OR Danish OR Spain OR Spanish OR Australia OR Australian OR “New Zealand”)

A4.1.2. Article screening

Title and abstract screening was carried out by MWJ in MS Excel. Article full texts were searched for in Google Scholar, Web of Science and the University of Oxford’s online library portal. Citations for full texts that could not be found are provided online (Jordon, 2022). All full text screening was carried out in MS Excel by MWJ, with one exclusion reason given per article in the order of Population, Intervention, Comparator, Outcome, Location, Duplicate or Review article, available online (Jordon, 2022). Inclusion and exclusion criteria for title, abstract and full text screening are given in Table A4.4.

Table A4.4. Inclusion and exclusion criteria for title, abstract and full text screening of articles identified by systematic literature search

	Rotational grazing (RG)	**Herbal leys (HL)**
Population	*Included*: pasture systems, including research stations, experimental plots, field trials and working farms. Can be grazed by sheep or cattle (ungrazed treatments acceptable for herbal ley treatments where outcome is herbage dry matter) *Excluded*: greenhouse, pot, mesocosm or laboratory experiments, long-term plant diversity plots. Pasture systems grazed by goats, deer, or other herbivores.	
Intervention	*Included*: any grazing practice that includes a rest period for the pasture within the grazing season, i.e. livestock rotated between paddocks or fields allowing an ungrazed recovery period. *Excluded*: studies that only consider different livestock stocking densities or grazing intensities, without any pasture rest period or rotation. Studies that simulate different grazing practices with mowing or cutting rather than with animals.	*Included*: a non-clover perennial forb (e.g. chicory, lucerne, trefoil) present in the pasture sward, either in isolation or in combination with other forbs, grasses and/or clovers. Can be sown or naturally occurring. *Excluded*: studies that only consider combinations of grasses and clovers, need to include other forb species.
Comparator	*Included*: continuous grazing (also known as set stocking) where there is no pasture rest period during the grazing season when livestock are temporarily excluded, or rotational grazing with different grazing or rest periods or stocking density to the Intervention	*Included*: a sward with a different species composition, typically without or with a different perennial forb species to the Intervention *Excluded*: multiple aspects of the treatment differed in a non-factorial manner, or no comparator

	Excluded: multiple aspects of the treatment differed in a non-factorial manner, or no comparator	
Outcomes	*Included*: Soil organic carbon, soil organic matter or soil total carbon (where soils are shown to be free of carbonates), either as a concentration (g/100g) or stock (t/ha) *Excluded*: studies that only measure carbon flux of pasture, or only present other chemical, physical or biological properties of soil, or only measure root carbon or carbon inputs to soil	
	Included: agricultural productivity metric; herbage dry matter yield (t.ha^{-1}), livestock daily liveweight gain (g.day^{-1}), milk yield (kg.day^{-1}), and sheep wool growth (mg.cm^{-2}.day^{-1} or g.day^{-1}). Sheep faecal egg count (eggs.g^{-1}) also extracted where presented, but this alone was insufficient for inclusion. *Excluded*: studies that only present other properties of herbage, such as chemical composition, or other properties of livestock, such as eating quality or fecundity	
Location	*Included*: studies in the British Isles (including Ireland), Belgium, Netherlands, Luxembourg and New Zealand (entirely temperate oceanic climate, Cfb Köppen-Geiger classification (Peel et al., 2007)). Also studies in Cfb regions of France, Germany, Spain, Denmark and Australia. Excluded: studies in non-Cfb regions of France, Germany, Spain, Denmark and Australia. Initial conservative exclusion from specification of study climate in title, abstract or full text, and inspection of study location for Spain and Australia. Full exclusion using Peel et al. (2007). Köppen-Geiger raster and study degrees decimal coordinates.	

A4.1.3. Data extraction and critical appraisal

Data was extracted directly from relevant studies to a predefined data extraction form in MS Excel by MWJ, who checked for errors and consistency of coding decisions during extraction. The complete spreadsheets of extracted data from relevant studies is provided online (Jordon, 2022). We extracted within-treatment standard errors (SE) for measurement estimates where available, converting from standard deviations (SD) if required using the following formula:

$$SE = \frac{SD}{\sqrt{n}}$$

where *n* is the sample size. If measures of variability presented were between-treatment only, these were not extracted. Where treatments not of interest were included factorially in a study with treatments of interest, we averaged outcome data across the treatments not of interest and only included these in the extracted data. Where study location was not specified in the article but the author affiliation was a research station, we assumed the study was located there. For studies that

presented outcome data over multiple years or grazing seasons, we averaged across years/seasons and only extracted this average, accounting for estimate standard errors where provided using the *rma.mv* function in the R package *metafor* (Viechtbauer, 2010). Where outcome data were presented in figures, these were extracted using the online platform *WebPlotDigitizer* (Rohatgi, 2020). Where multiple relevant measures of productivity were given in a single study, these were all extracted. However, liveweight gain data was primarily extracted for younger classes of stock that were yet to reach mature weight; where weights or liveweight change studies were for mature livestock (i.e. breeding ewes or cows), these were generally not extracted. We harmonised productivity outcomes to the same units (Table 6.2) where possible. Where milk yield was presented as litres per day, we converted this to $kg.day^{-1}$ using the conversion factor 1L = 1.03 kg. However, we extracted two units for wool growth ($mg.cm^{-2}.day^{-1}$ and $g.day^{-1}$) due to the difficulty of converting between these and analysed them separately. Where soil organic carbon (SOC) values were presented as stocks ($t.ha^{-1}$), we converted these to concentration ($g.100g^{-1}$) using the formula:

$$SOC\ conc\ (g.100g^{-1}) = \frac{SOC\ stock\ (ha)}{Bulk\ density\ (g.cm^{-1})\ x\ Soil\ sampling\ depth\ (cm)}$$

When harmonising stocking density to livestock units (LU) per ha (Defra, 2010, SAC Consulting, 2020), 1 dry sheep equivalent (DSE, corresponding to a Merino wether) was assumed to be equivalent to 0.08 LU.

Study critical appraisal was carried out alongside data extraction using a scoring system (Table A4.5). We aggregated these scores into three categories:

- Low validity: studies with a score of 0 in one or more categories

- Unclear validity: the information required to allocate a score for one or more categories was not available in the article
- High validity: scores of 1 or above in all categories

The scores allocated for each category and the overall critical appraisal score are recorded for each study in the final datasets, available online (Jordon, 2022). All studies were included in the meta-analysis, but sensitivity analyses were conducted excluding studies of low and unclear validity to test if study quality influenced model outputs.

Table A4.5. Critical appraisal criteria used to score relevant studies, adapted from Haddaway et al. (2017a)

Variable	**Value**	**Score**†
Spatial (true) replication	1 replicate	0
	2 replicates	1
	≥ 3 replicates	2
Individual animals per treatment (where applicable)	< 10 individuals	0
	10 – <30 individuals	1
	≥ 30 individuals	2
Treatment allocation	Purposive (selective)	0
	Split-plot/latin square/ blocked/randomised	2
Duration of experiment	< 6 weeks	0
	6 weeks – <2 years	1
	2 years – 4 years	2
	≥ 5 years	3

† Where insufficient information is given to assign a score, a "?" is used

A4.1.4. Requests for missing data

Where required data was missing from study articles (Tables A4.6 & A4.7), we attempted to contact the corresponding author of the article, using the following email template:

Dear Prof/Dr [name],

I am a PhD student at the University of Oxford. I am conducting a systematic review (following Collaboration for Environmental Evidence guidelines) on the agricultural productivity impacts of including perennial fodder herbs in temperate pastures, in collaboration with Dr Gillian Petrokofsky and Prof Kathy Willis.

I am including your study "[title]" published in [year] in the meta-analysis, and am contacting you to request if you could please provide some additional information to fully parametrise the analysis.

In particular, do you have any information on [delete as appropriate]

- Within-treatment standard error or standard deviations for the [productivity] measurements located in Table [x].
- The seed mixtures (kg/ha) used to create each treatment, or herbage biomass of individual species (% or t/ha) within treatments (herbal ley studies only)
- Stocking density/number of paddocks/grazing and rest periods/length of grazing season (rotational grazing studies only)
- The number of animals allocated to each treatment/number of soil samples taken to estimate soil carbon/number of herbage samples taken
- Soil bulk density at the study site
- The coordinates of the study site
- The year(s) the study was conducted in

I would be very grateful if you could send me any of this information and would include you in the acknowledgments of the paper when written up. I am happy to get information from other published research articles where applicable if you could point

me to these. It would also be useful to know if these data were not measured in your study or you no longer have access to the data.

Thank you very much.

Best wishes,

Matt

We thank authors who supplied additional information in the Acknowledgments of Chapter 5.

Table A4.6. Required data missing from rotational grazing studies. P: information provided in study article, M: information missing from study article, MP: information missing from study article but provided by author upon request, n/a: information not relevant to that study. We also indicate whether an email address was provided for the corresponding author, and whether our email successfully sent to this address.

Unique article ID	Soil bulk density	Soil samples	Number of yield samples/ animals per treatment	Yield endline error	Stocking density	Number of paddocks	Grazing/rest periods	Length of grazing season	Author email available	Author responded
2021RGHL 010	MP	P	P	P	P	P	P	P	Yes	Yes
2021RGHL 027	P	MP	n/a	n/a	P	P	P	P	Yes	Yes
2021RGHL 045	n/a	n/a	M	M	P	P	P	P	Yes	No
2021RGHL snow058	n/a	n/a	M	M	P	M	P	P	Yes	Email bounced
2021RGHL snow059	n/a	n/a	P	M	M	P	P	P	Yes	Email bounced
2021RGHL snow061	n/a	n/a	P	M	P	P	P	P	No	n/a
2021RGHL snow067	n/a	n/a	P	M	P	P	P	P	Yes	Email bounced
2021RGHL snow077	n/a	n/a	P	P	P	P	P	P	n/a	n/a
2021RGHL snow078	n/a	n/a	P	P	P	P	M	M	No	n/a
2021RGHL snow079	n/a	n/a	P	P	P	P	P	P	n/a	n/a
2021RGHL snow080	n/a	n/a	P	P	P	P	P	P	n/a	n/a

2021RGHL snow081	n/a	n/a	P	M	P	P	P	P	No	n/a
2021RGHL snow082	n/a	n/a	P	M	P	P	M	P	No	n/a
2021RGHL snow093	n/a	n/a	P	M	P	P	M	P	No	n/a
2021RGHL snow121	n/a	n/a	P	M	P	P	P	P	No	n/a
2021RGHL snow094	n/a	n/a	P	P	M	P	P	P	No	n/a
2021RGHL snow096	n/a	n/a	P	M	P	P	P	P	No	n/a
2021RGHL snow103	n/a	n/a	M	M	P	P	P	P	No	n/a
2021RGHL snow125	n/a	n/a	P	P	P	P	P	P	n/a	n/a
2021RGHL snow148	n/a	n/a	P	M	P	P	P	P	Yes	Yes
2021RGHL snow158	n/a	n/a	P	P	P	P	P	P	n/a	n/a

Table A4.7. Required data missing from herbal ley studies. P: information provided in study article, M: information missing from study article, MP: information missing from study article but provided by author upon request, n/a: information not relevant to that study. We also indicate whether an email address was provided for the corresponding author, and whether our email successfully sent to this address.

Unique Study ID	**Study site coordinates**	**Year study conducted**	**Number of yield samples/animals per treatment**	**Seed mix**	**Yield endline error**	**Author email available**	**Author responded**
2021RGHL006	P	P	P	P	P	n/a	n/a
2021RGHL017a	MP	P	P	MP	M	Yes	Yes
2021RGHL017b	MP	P	P	MP	M	Yes	Yes
2021RGHL017c	MP	P	P	MP	M	Yes	Yes
2021RGHL029	P	P	P	P	P	n/a	n/a
2021RGHL039	P	P	P	P	P	n/a	n/a
2021RGHL044	P	P	P	M	M	Yes	No
2021RGHLsnow 051	P	P	P	P	M	Yes	No
2021RGHLsnow 060	P	P	P	P	M	Yes	No
2021RGHLsnow 063a	P	P	P	P	M	No	n/a
2021RGHLsnow 063b	P	P	P	P	M	No	n/a
2021RGHLsnow 065	P	P	P	P	M	No	n/a
2021RGHLsnow 066	P	P	P	P	P	n/a	n/a
2021RGHLsnow 072a	P	P	P	P	M	Yes	No
2021RGHLsnow 072b	P	P	P	P	M	Yes	No

2021RGHLsnow 072c	P	P	P	P	M	Yes	No
2021RGHLsnow 072d	P	P	P	P	M	Yes	No
2021RGHLsnow 072e	P	P	P	P	M	Yes	No
2021RGHLsnow 072f	P	P	P	P	M	Yes	No
2021RGHLsnow 074	P	P	P	P	P	n/a	n/a
2021RGHLsnow 075a	P	P	P	M	M	No	n/a
2021RGHLsnow 075c	P	P	P	P	M	No	n/a
2021RGHLsnow 083	P	P	P	M	P	No	n/a
2021RGHLsnow 087	P	P	P	P	P	n/a	n/a
2021RGHLsnow 088a	P	P	P	M	M	No	n/a
2021RGHLsnow 088b	P	P	P	M	M	No	n/a
2021RGHLsnow 090	P	P	P	P	P	n/a	n/a
2021RGHLsnow 111	P	P	P	P	P	n/a	n/a
2021RGHLsnow 091	P	P	P	P	M	Yes	Email bounced
2021RGHLsnow 092	P	P	P	P	P	n/a	n/a
2021RGHLsnow 095	P	P	P	P	P	n/a	n/a
2021RGHLsnow 098	P	P	P	P	M	Yes	No
2021RGHLsnow 099a	P	P	P	P	M	Yes	No
2021RGHLsnow 099b	P	P	P	P	M	Yes	No
2021RGHLsnow 100	P	P	P	P	P	n/a	n/a
2021RGHLsnow 102	P	P	P	P	P	n/a	n/a
2021RGHLsnow 144a	P	P	P	P	M	No	n/a
2021RGHLsnow 144b	P	P	P	P	M	No	n/a
2021RGHLsnow 144c	P	P	P	P	M	No	n/a
2021RGHLsnow 144d	P	P	P	P	M	No	n/a
2021RGHLsnow 144e	P	P	P	P	M	No	n/a
2021RGHLsnow 105	P	P	P	M	P	No	n/a
2021RGHLsnow 106	P	P	P	M	P	No	n/a
2021RGHLsnow 107	P	M	P	P	P	No	n/a

2021RGHLsnow 108	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 110a	P	P	P	P	M	No	n/a
2021RGHLsnow 110b	P	P	P	P	M	No	n/a
2021RGHLsnow 110c	P	P	P	P	M	No	n/a
2021RGHLsnow 113	P	P	P	P	M	Yes	Email bounced
2021RGHLsnow 114	P	P	P	P	P	n/a	n/a
2021RGHLsnow 117	P	P	P	P	P	n/a	n/a
2021RGHLsnow 118	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 119a	P	P	P	P	M	No	n/a
2021RGHLsnow 119b	P	P	P	P	M	No	n/a
2021RGHLsnow 120	P	P	P	P	M	Yes	Email bounced
2021RGHLsnow 123	P	P	P	M	M	Yes	Yes
2021RGHLsnow 124	P	P	P	P	M	No	n/a
2021RGHLsnow 126a	P	M	P	P	P	Yes	Email bounced
2021RGHLsnow 126b	P	M	P	P	P	Yes	Email bounced
2021RGHLsnow 126c	P	P	P	P	P	n/a	n/a
2021RGHLsnow 127	P	M	P	M	P	Yes	Email bounced
2021RGHLsnow 128	P	P	P	P	P	n/a	n/a
2021RGHLsnow 129a	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 129b	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 129c	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 130	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 132	P	P	P	P	P	n/a	n/a
2021RGHLsnow 133	P	P	P	P	M	No	n/a
2021RGHLsnow 134	P	P	P	M	M	No	n/a
2021RGHLsnow 136a	P	P	P	M	P	No	n/a
2021RGHLsnow 136b	P	P	P	M	P	No	n/a
2021RGHLsnow 137	P	P	P	P	M	Yes	Email bounced
2021RGHLsnow 138	P	P	P	M	M	No	n/a

2021RGHLsnow 139	P	P	P	M	P	Yes	Email bounced
2021RGHLsnow 140	P	M	P	P	P	No	n/a
2021RGHLsnow 142	P	P	P	P	P	n/a	n/a
2021RGHLsnow 143	P	M	P	M	M	Yes	Email bounced
2021RGHLsnow 145	P	P	P	P	P	n/a	n/a
2021RGHLsnow 146	P	P	P	P	M	No	n/a
2021RGHLsnow 147	M	P	P	P	M	No	n/a
2021RGHLsnow 149	P	P	P	M	M	No	n/a
2021RGHLsnow 151a	P	P	P	P	M	No	n/a
2021RGHLsnow 151b	P	P	P	P	M	No	n/a
2021RGHLsnow 153a	P	P	P	M	M	Yes	Email bounced
2021RGHLsnow 153b	P	P	M	M	P	Yes	Email bounced
2021RGHLsnow 155	P	P	P	P	M	No	n/a
2021RGHLsnow 157a	P	P	P	M	P	No	n/a
2021RGHLsnow 157b	P	P	P	M	P	No	n/a
2021RGHLextra 159	P	P	P	P	P	n/a	n/a

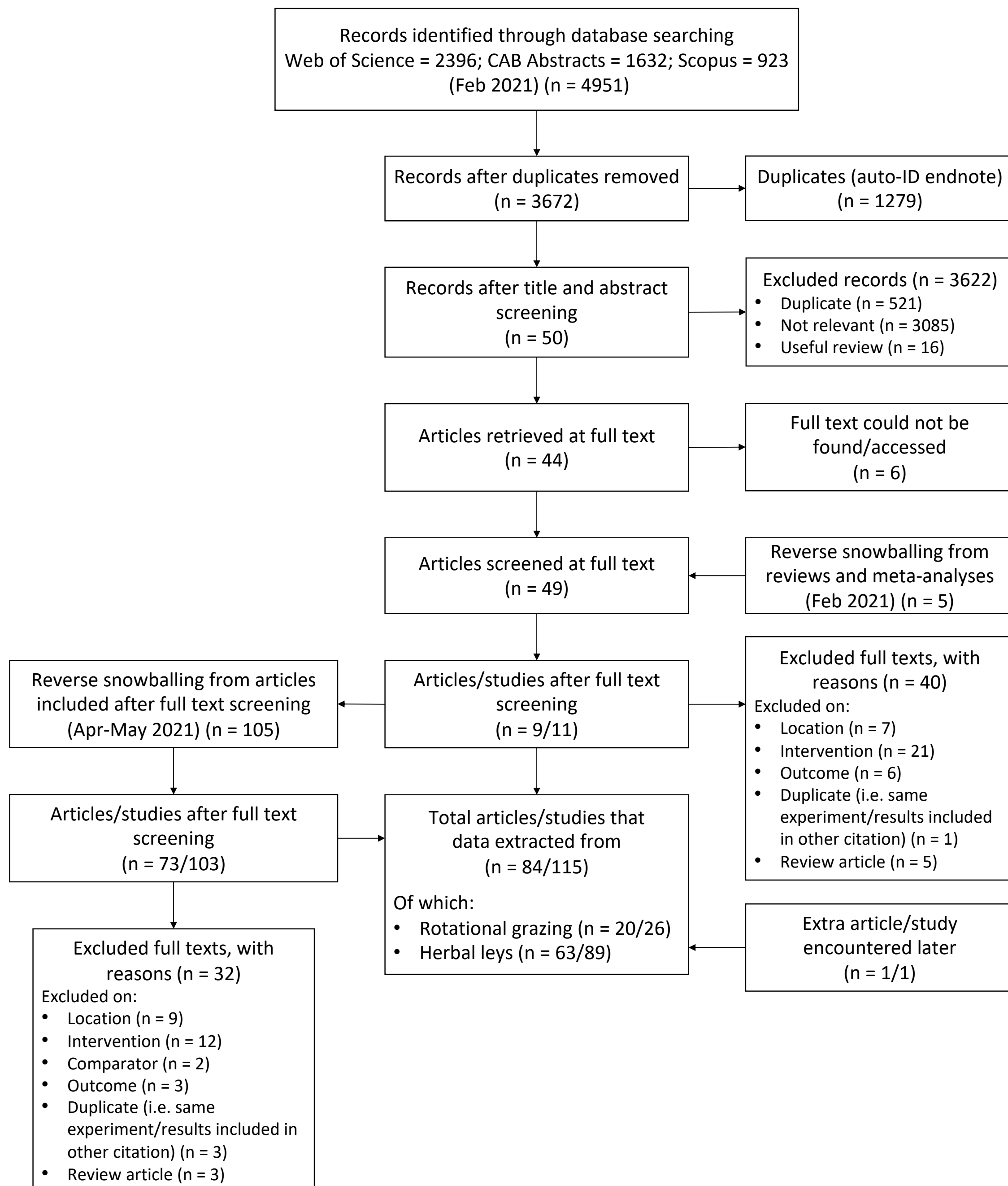


Figure A4.1. The literature searching, reverse snowballing, and screening process, with the number of records included and excluded at each stage. For articles excluded at the full text screening stage, the number excluded for each reason are also given. This flow chart follows the template of (Haddaway et al., 2017b).

A4.2. Meta-analysis methods and results

A4.2.1. Calculating aggregated plant traits for mixed swards

We queried the TRY plant trait database (Kattge et al., 2020) for all species included in study treatment sward compositions from our systematic review and the traits of rooting depth (m), plant nitrogen fixation capacity (yes/no), leaf nitrogen content per leaf dry mass ($mg.g^{-1}$) as a proxy for herbage crude protein content, and leaf tannin content per leaf dry mass ($mg.g^{-1}$). The species searched for, trait values returned (averaged where multiple observations were available in TRY), and species-trait combinations where data was unavailable are provided online (Jordon, 2022). Because some species-trait combinations only had one observation present in TRY, whereas others had many observations (which we averaged) or entries were of a 'species mean' value, we conducted a sensitivity analysis excluded treatments with trait values that came from single values (root depth) or were averaged across five individual values or less (leaf nitrogen content).

To aggregate trait values across all species present in a treatment sward, we extracted seed mixes used to establish treatments or herbage composition measurements from studies. Herbage composition (expressed either as herbage biomass for each species or as a percentage of the overall biomass) was used to directly weight trait values. Where only seed mix information was available (typically presented as $kg.ha^{-1}$ seed of each species present), seed weight (mg) data from the Ecoflora database (Fitter and Peat, 1994) was used to calculate $seeds.kg^{-1}$ for each species. This was used to infer the relative number of individuals of each species per hectare to weight trait values. We also used these relative abundances to calculate species evenness (inverse Simpson's diversity index) and recorded species richness

(individual varieties or cultivars were not classed as separate species). Although seed mix is a weak proxy of the relative abundance of species once a sward has established, we felt this was a necessary approximation and tested the influence of using seed mix vs herbage biomass to weight trait values in a sensitivity analysis. To aggregate plant nitrogen fixation capacity in the absence of quantitative values for nitrogen fixation, we scored species nitrogen fixation as 1 (yes) or 0 (no) and aggregated this score. To test the appropriateness of this aggregation process, we ran a further sensitivity analysis across study treatments that were monocultures, i.e. only one species so trait values were not aggregated.

Our calculations of aggregate trait values for each sward composition are available online in individual spreadsheets per study and the aggregate trait scores calculated are presented in the final dataset (Jordon, 2022). Where seed weight or trait data was not available for all species present in a treatment sward this was recorded in the dataset and we ran a sensitivity analysis assessing the influence of observations where species were missing from aggregate trait scores on our results. Where no information was available from the article on relative abundance of sward composition, these studies were excluded from the analysis, apart from perennial ryegrass (PRG)-white clover (WC) mixes where an approximate average was used from studies that did present this information of 20kg.ha^{-1} PRG, 3 kg.ha^{-1} WC, to avoid having to exclude these observations.

A4.2.2. Imputation and sensitivity analyses

Studies identified by our systematic review frequently failed to report measures of within-treatment variation for outcome estimates analysed above. For example, from

studies of herbal leys in our dataset with all desired predictor variables available, of 174 observations of herbage dry matter and 184 observations of livestock liveweight gain, only 58 and 103 have within-treatment standard errors available, respectively. Discarding data with missing values risks biasing meta-analyses unless values are missing at random (Weir et al., 2018). Therefore, we used multiple imputation methods to fill missing standard errors, which has the advantage of explicitly representing the variability associated with the imputation process in the meta-analysis (Lajeunesse, 2013).

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* (van Buuren and Groothuis-Oudshoorn, 2011). To test the sensitivity of our results to this imputation method (**EI**, errors imputed), we repeat each analysis only including observations where errors are present (**EP**). We discuss EI model outputs in the Results section of Chapter 5 and present EP results in Appendix 4.2.5 for comparison. However, for some of our analyses, there were too few standard errors reported in the input data to fit a model just on these observations or for *mice* to impute missing values. In these instances, we weighted the response variable by the sample size (n) of each observation using the *weights* argument in *brms* (**WN**, weighted by n).

We tested the sensitivity of our results to study quality using the critical appraisal (**CA**) scores assigned during our systematic review (Table A4.5, Appendix 4.1.3). We ran additional analyses excluding studies of low or unclear validity, i.e. with one or a combination of: only one spatial replicate, less than 10 animals per treatment

(where applicable), selective rather than randomised or blocked treatment allocation, and/or a study duration of under six weeks. CA sensitivity analyses were not conducted for the Herbal Ley wool growth or tannin analyses due to limited data availability resulting in these results needing to be treated with caution regardless.

In addition, we ran a series of sensitivity analyses to test our data preparation methodology for the Herbal Leys analyses (Section 6.4.2.2):

1. Seed mix validity (**SMV**). Excludes aggregated trait scores using seed mix data to weight trait values to test sensitivity of results to the weak inference of plant abundance and contribution to forage available to stock from this approach; only includes 'direct' observations based on herbage biomass, plant counts or monocultures.
2. Aggregation validity (**AV**). Tests suitability of approach to aggregating traits in multi-species swards by running model only on mono-species treatments, such that trait values are directly from the TRY database rather than a weighted average across multiple species.
3. Trait score validity (**TSV**). Assesses sensitivity of results to quality of data from TRY database. Excludes observations where trait values for species present in the treatment sward are only from a single observation in TRY (root depth) or averaged from five or less observations (leaf N). The species classed as having low TSV were prairie grass, smooth brome, upland brome, meadow fescue, sorrel, alsike clover, subterranean clover, caucasian clover, white clover and greater birdsfoot trefoil.
4. Missing data (**MD**). Where seed weight or trait data were missing for a small number of species in a diverse sward, aggregate trait scores were calculated

based on the species where data was available, and the species missing recorded in the datasheet. Further, for perennial ryegrass-white clover swards which did not specify sowing proportions, an approximate average was used from studies that did present this information of 20kg.ha^{-1} PRG, 3 kg.ha^{-1} WC. The missing data analysis excluded these observations, to test the sensitivity of the results to this.

For the Rotational grazing analyses, where required information on grazing and rest periods were not available in the study article, these observations were excluded from analysis rather than included then their effect tested in a MD analysis. The results of all sensitivity analyses are presented in Appendix 4.2.5.

A4.2.3. Model fitting

Table A4.8. Details of brm sampling when fitting models

Intervention	Outcome	Model	Results	Chains	Iterations‡	Warmup samples‡	Total post-warmup samples
Rotational grazing	Herbage DM	WN: all	Table 6.3	4	2000	1000	4000
		WN: CA	Table A4.9	4	2000	1000	4000
	DLWG	EI: all	Table 6.3	40†	2000	1000	40000
		EP: all	Table A4.9	4	2000	1000	4000
Herbal leys	Herbage DM	EI: all	Table 6.4	40†	8000	4000	160000
		EP: all	Table A4.10	4	2000	1000	4000
		EI: CA	Table A4.10	40†	8000	4000	160000
		EI: SMV	Table A4.10	40†	8000	4000	160000
		EI: AV	Table A4.10	40†	8000	4000	160000
		EI: TSV	Table A4.10	40†	8000	4000	160000
		EI: MD	Table A4.10	40†	8000	4000	160000
	DLWG	EI: all	Table 6.4	40†	2000	1000	40000

		WN: Herbage DM	Table 6.4	4	2000	1000	4000
		EP: all	Table A4.10	4	2000	1000	4000
		WN: CA	Table A4.10	4	2000	1000	4000
		EI: SMV	Table A4.10	40†	2000	1000	40000
		EI: AV	Table A4.10	40†	2000	1000	40000
		EI: TSV	Table A4.10	40†	2000	1000	40000
		EI: MD	Table A4.10	40†	2000	1000	40000
	Wool growth	EP: all (mg.cm^{-2}.day^{-1})	Table 6.4	4	8000	4000	16000
		EP: all (g.day^{-1})	Table 6.4	4	8000	4000	16000
	DLWG (tannin analysis)	EI: tannin*PEG	Table 6.5	40†	2000	1000	40000
		EI: tannin*leaf N	Table 6.5	40†	2000	1000	40000
		EI: FEC	Table 6.5	40†	2000	1000	40000
		EP: tannin*PEG	Table A4.11	4	2000	1000	4000
		EP: tannin*leaf N	Table A4.11	4	2000	1000	4000
		EP: FEC	Table A4.11	4	2000	1000	4000
	Faecal egg count	WN: all	Table 6.5	4	2000	1000	4000

‡per chain
†4 chains per imputed dataset, 10 imputed datasets

A4.2.3.1. Summary outputs for main models

Rotational grazing – Herbage DM (WN: all)

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | weights(Yield_endline_n, scale = FALSE) ~ RG_proportion_rest_period_centred + Latitude_centred + (1 |
Unique_Study_ID)
   Data: RG_HerbageDM_MD_centred (Number of observations: 19)
  Draws: 4 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 4000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 9)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)     3.59      0.96     2.28     5.82 1.00      963     1373

Population-Level Effects:
                                  Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                             3.99      1.12     1.89     6.21 1.00      996     1080
RG_proportion_rest_period_centred     0.31      0.01     0.28     0.33 1.00     2615     1970
```

```
Latitude_centred               -0.07     0.18   -0.40     0.31 1.00     1152     1497

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma     0.33      0.00     0.33     0.34 1.00     2876     1951

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Rotational grazing – DLWG (EI: all)

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | se(Yield_endline_error, sigma = TRUE) ~ RG_proportion_rest_period_centred * Livestock_unit_per_ha_centred + Stock_cat + (1 | Unique_Study_ID)
   Data: RG_LiveweightGain_MD_centred_IMPerror (Number of observations: 35)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 8)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)   108.10     35.69    61.91   197.20 1.01    11411    16222

Population-Level Effects:
                                                            Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                                                     -39.37     65.45  -179.07    80.09 1.02     1920    14972
RG_proportion_rest_period_centred                             221.16    112.02     2.18   447.92 1.03      764    15712
Livestock_unit_per_ha_centred                                 -11.14      5.53   -22.37    -0.40 1.04      602     7793
Stock_catB_cattle                                             787.05     96.18   595.69   977.81 1.00    16496    18282
RG_proportion_rest_period_centred:Livestock_unit_per_ha_centred    20.78     10.28     0.78    41.56 1.04      634    13858

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma    14.14      4.95     5.40    25.44 1.06      398      529

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Herbal leys – Herbage DM (EI: all)

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | se(Yield_endline_error, sigma = TRUE) ~ Aggregated_root_depth_m_centred * Aggregate_proportion_legume_centred + Species_richness_centred +
Species_evenness_inverse_Simpsons_centred + Latitude_centred + (1 | Unique_Study_ID)
   Data: HL_HerbageDM_centred_IMPerror (Number of observations: 174)
  Draws: 40 chains, each with iter = 8000; warmup = 4000; thin = 1;
         total post-warmup draws = 160000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 41)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)     5.77      0.70     4.59     7.30 1.00    19437    39815

Population-Level Effects:
                                                          Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                                                     7.97      0.97     6.05     9.86 1.00    15598    27886
Aggregated_root_depth_m_centred                               1.63      0.65     0.36     2.89 1.01     1940    25095
Aggregate_proportion_legume_centred                           2.20      0.48     1.26     3.14 1.03      809     5194
Species_richness_centred                                      0.13      0.09    -0.04     0.29 1.01     2362    80128
Species_evenness_inverse_Simpsons_centred                     2.76      0.92     0.95     4.56 1.03      739     6036
Latitude_centred                                             -0.55      0.18    -0.90    -0.20 1.00    20063    35930
Aggregated_root_depth_m_centred:Aggregate_proportion_legume_centred     2.33      1.49    -0.61     5.27 1.00    19187   106842

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma     1.44      0.12     1.21     1.69 1.09      274      802

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Herbal leys – DLWG (EI: all)

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | se(Yield_endline_error, sigma = TRUE) ~ Aggregated_root_depth_m_centred + Aggregated_leaf_N_mg.g.1_centred +
Species_richness_centred + Species_evenness_inverse_Simpsons_centred + Latitude_centred + (1 | Unique_Study_ID)
   Data: HL_LiveweightGain_sheep_centred_IMPerror (Number of observations: 184)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 46)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)    70.80      9.27    54.54    90.98 1.00     9449    15374
```

```
Population-Level Effects:
                                       Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                                188.11     11.18   166.11   210.08 1.00     7428    13246
Aggregated_root_depth_m_centred          -36.32     14.52   -64.41    -7.28 1.00    35597    28705
Aggregated_leaf_N_mg.g.1_centred           3.50      0.67     2.17     4.82 1.00    31929    30225
Species_richness_centred                   4.72      8.87   -12.47    22.20 1.00    24246    28716
Species_evenness_inverse_Simpsons_centred -12.48    39.90   -91.54    64.90 1.00    25174    29107
Latitude_centred                           5.43      2.40     0.74    10.17 1.00     9616    15466

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma    45.96      3.13    40.29    52.53 1.00    24988    29086

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Herbal leys – DLWG (EI: tannin*PEG)

```
 Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | se(Yield_endline_error, sigma = TRUE) ~ Tannin_est_centred * PEG_all_LWG + Latitude_centred + (1 | Unique_Study_ID)
   Data: HL_tannin_LWG_centred_IMPerror (Number of observations: 45)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 15)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)    63.13     16.45    36.03   101.10 1.00    12444    20669

Population-Level Effects:
                               Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                        158.11     19.28   120.38   196.76 1.00    14719    21145
Tannin_est_centred                 0.74      0.56    -0.38     1.86 1.00    29801    26582
PEG_all_LWGYes                   -10.14     22.12   -54.51    32.43 1.00    32147    27122
Latitude_centred                 -28.05     13.69   -55.33    -0.90 1.00    19696    21662
Tannin_est_centred:PEG_all_LWGYes  0.45      0.82    -1.15     2.06 1.00    29637    27413

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma    53.72      8.34    39.85    72.30 1.00    19817    24256

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Herbal leys – DLWG (EI: tannin*leaf N)

```
 Family: gaussian
  Links: mu = identity; sigma = identity
Formula: Yield_endline_est | se(Yield_endline_error, sigma = TRUE) ~ Tannin_est_centred * Aggregated_leaf_N_mg.g.1_centred + (1 | Unique_Study_ID)
   Data: HL_tannin_leafN_LWG_centred_IMPerror (Number of observations: 32)
  Draws: 40 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 40000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 13)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)    69.77     19.55    37.23   114.27 1.00    11259    14303

Population-Level Effects:
                                                 Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                                          170.19     30.55   109.81   230.59 1.00    11744    18119
Tannin_est_centred                                   1.41      1.72    -1.94     4.90 1.00    13168    18985
Aggregated_leaf_N_mg.g.1_centred                     7.73      8.90    -9.64    25.50 1.00    11699    17706
Tannin_est_centred:Aggregated_leaf_N_mg.g.1_centred  0.57      0.53    -0.46     1.61 1.00    12387    18550

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma    52.91     10.56    36.37    77.34 1.00    14670    16690

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

Herbal leys – FEC (WN)

```
Family: gaussian
  Links: mu = identity; sigma = identity
Formula: FEC_est | weights(FEC_n, scale = FALSE) ~ Wormer_all_LWG * Tannin_est_centred + Latitude_centred + (1 | Unique_Study_ID)
   Data: HL_FEC_tannin_wormer_centred (Number of observations: 34)
  Draws: 4 chains, each with iter = 2000; warmup = 1000; thin = 1;
         total post-warmup draws = 4000

Group-Level Effects:
~Unique_Study_ID (Number of levels: 13)
              Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sd(Intercept)   806.70    194.06   529.42  1293.09 1.01      970     1454

Population-Level Effects:
                                   Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
Intercept                           1302.06    244.61   801.89  1773.64 1.00     1123     1423
Wormer_all_LWGYes                   -818.05     57.15  -927.56  -705.69 1.00     2978     2380
Tannin_est_centred                     1.89      0.79     0.35     3.45 1.00     3754     2432
Latitude_centred                      -4.19     39.19   -80.63    70.12 1.00     1418     1584
Wormer_all_LWGYes:Tannin_est_centred  25.43      3.91    17.80    32.96 1.00     2713     2095

Family Specific Parameters:
      Estimate Est.Error l-95% CI u-95% CI Rhat Bulk_ESS Tail_ESS
sigma   397.07      5.80   385.65   408.68 1.00     3938     2685

Draws were sampled using sampling(NUTS). For each parameter, Bulk_ESS
and Tail_ESS are effective sample size measures, and Rhat is the potential
scale reduction factor on split chains (at convergence, Rhat = 1).
```

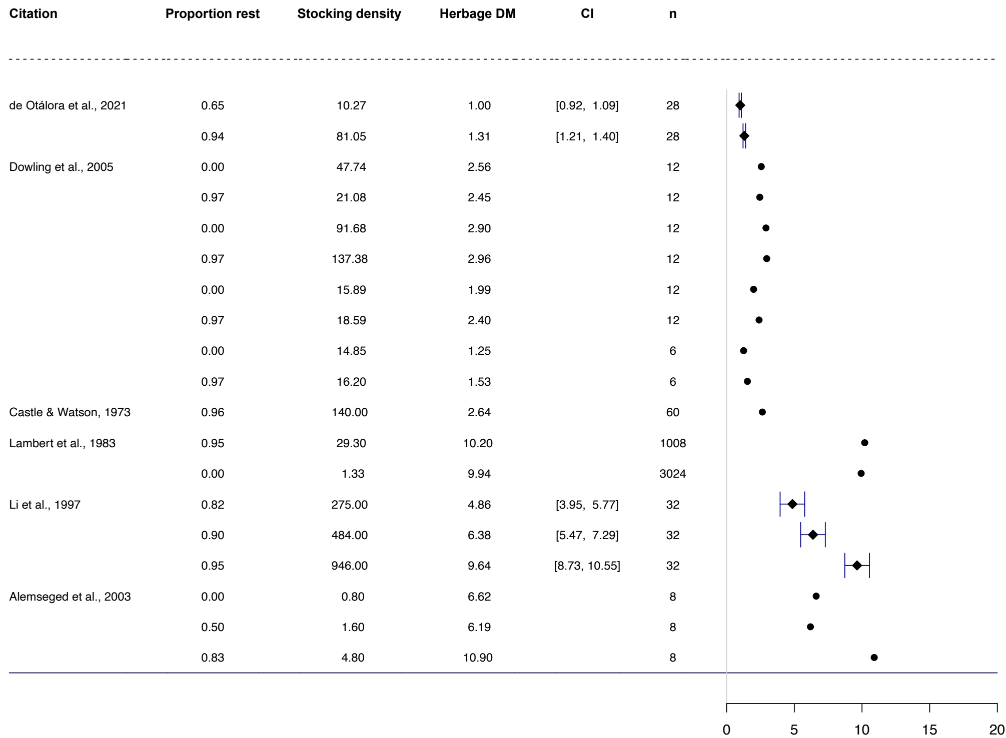
Note that indicators of non-convergence (Rhat > 1.05) are taken here as false-positives and reflect non-convergence between models fitted to each of the 10 imputed datasets rather than non-convergence within models.

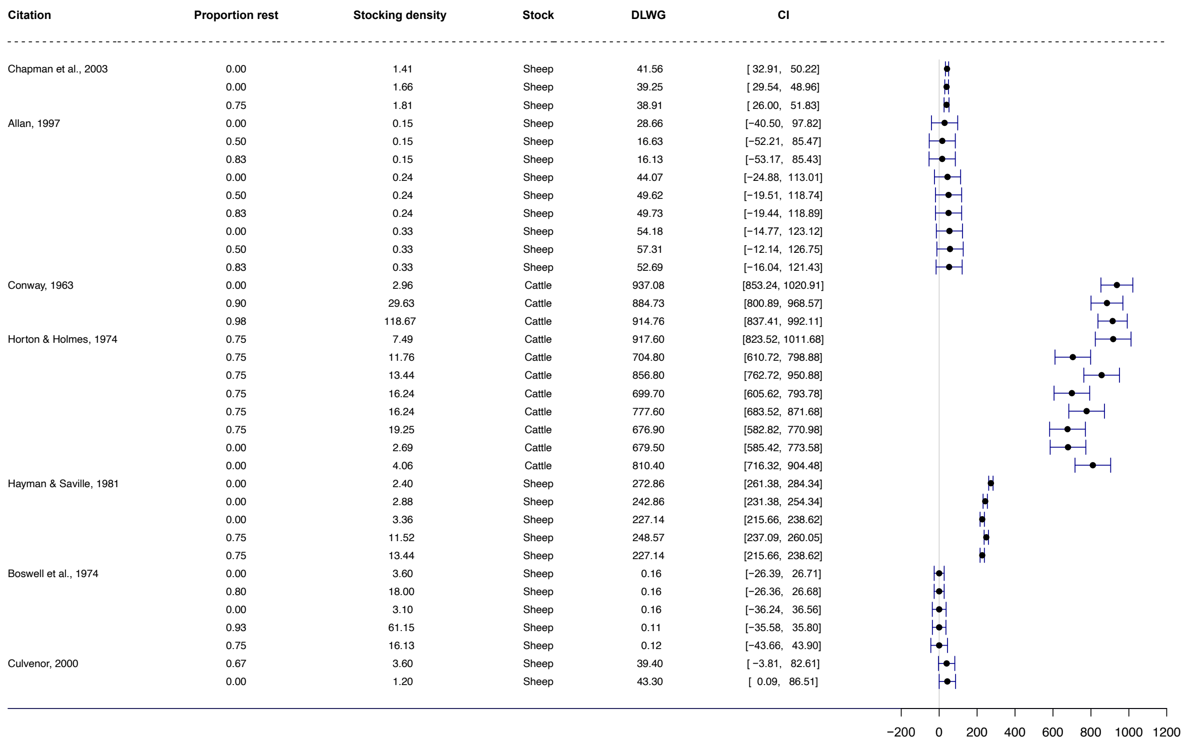
A4.2.4. Forest plots of raw data

A4.2.4.1. Rotational grazing

Forest plots showing estimates of **a**) herbage dry matter (DM, t.ha^{-1}) and **b**) livestock daily liveweight gain (DLWG, g.day^{-1}) from studies of rotational grazing identified by systematic review. Additional columns show the proportion of the grazing season the treatment was rested (0: continuous grazing, 1: continuous rest) and the stocking density in livestock units per hectare (LU.ha^{-1}) (Defra, 2010, SAC Consulting, 2020). Estimates with 95% confidence intervals are given for each treatment extracted from studies in the table and plotted adjacent for each row. For DLWG, these include confidence intervals calculated from imputed standard errors (SEs) for analysis (see Appendix 4.2.2). There were insufficient observations to impute missing SEs for

herbage DM, so this analysis was instead weighted by sample size (n) and estimates presented without confidence intervals in the forest plot.





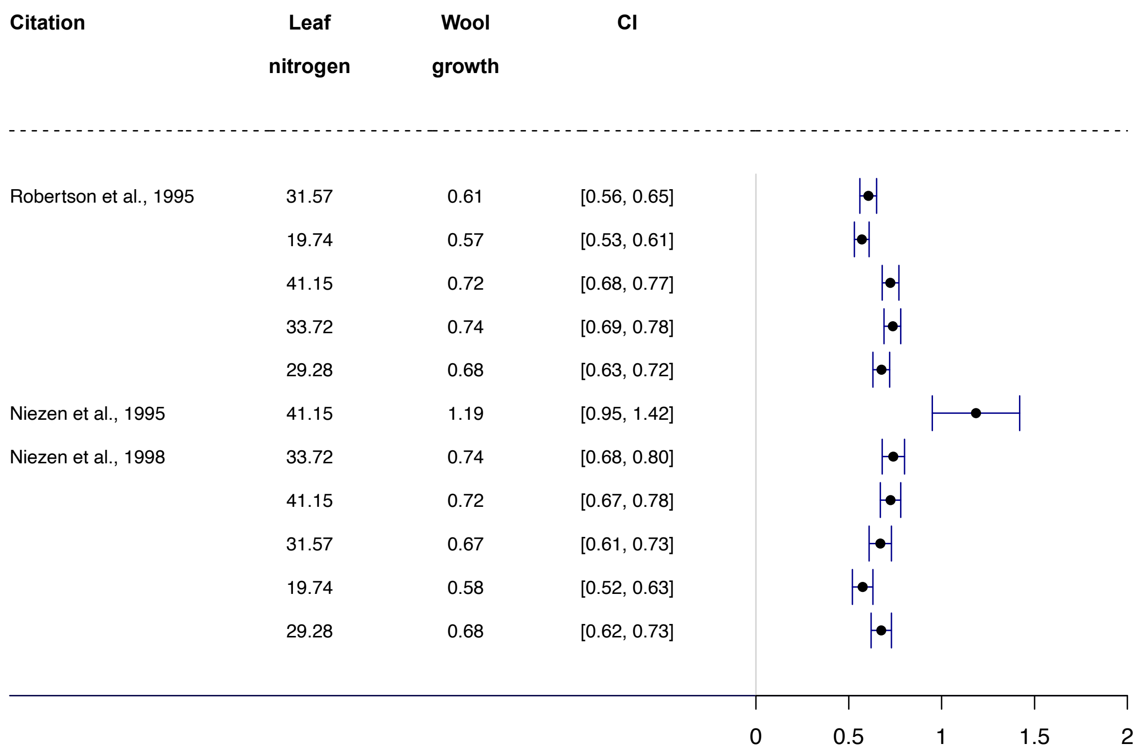
A4.2.4.2. Herbal leys

Forest plots showing estimates of **a**) herbage dry matter (DM, t.ha^{-1}), **b**) sheep daily liveweight gain (DLWG, g.day^{-1}), **c**) wool growth (mg.cm^{-2}.day^{-1}), and **d**) wool growth (g.day^{-1}) from studies of herbal leys identified by systematic review. Additional columns show the root depth (m), proportion of legumes, and leaf nitrogen content per leaf dry mass (mg.g^{-1}) of the sward weighted by the relative abundance of species present, and species richness and evenness (inverse Simpson's diversity index) (Appendix 4.2.1). Estimates with 95% confidence intervals are given for each treatment extracted from studies in the table and plotted adjacent for each row. For herbage DM and DLWG, these include confidence intervals calculated from imputed standard errors (SEs) for analysis (see Appendix 4.2.2).

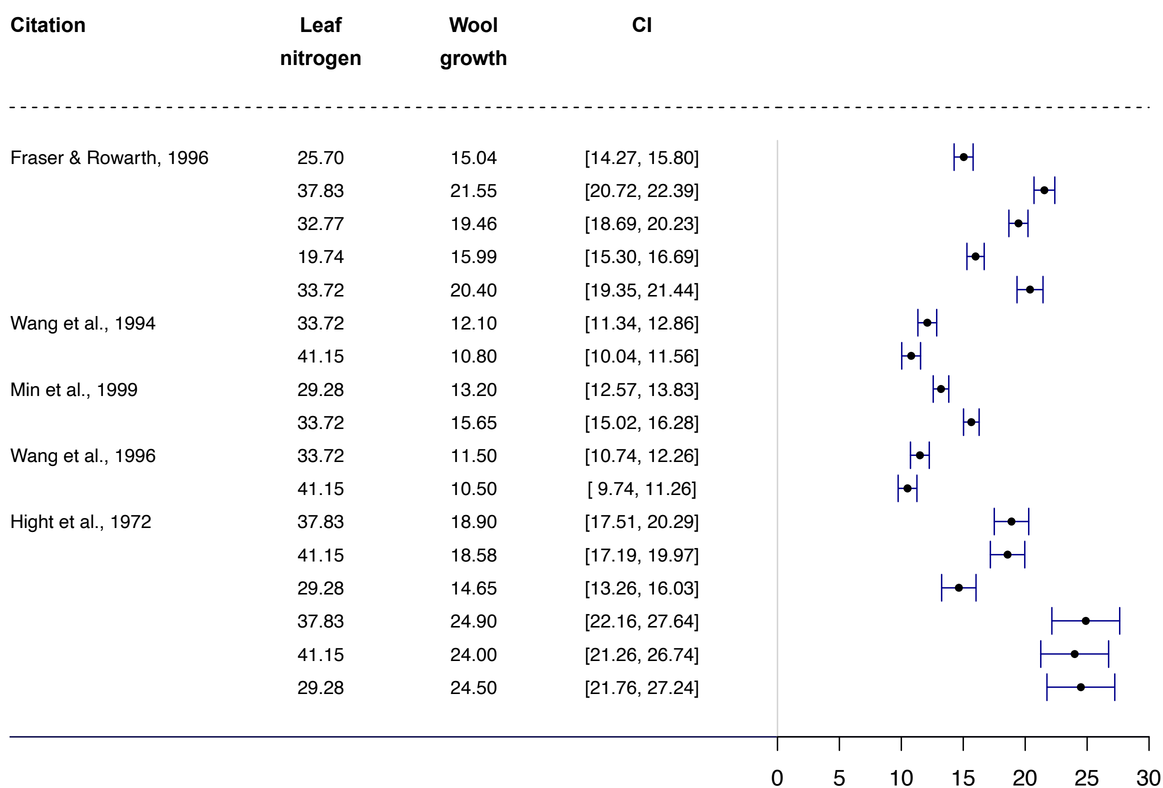
Citation	Root depth	Proportion legume	Species richness	Species evenness	Herbage DM	CI
Cong et al., 2014	0.75	0.00	1	0.00	2.04	[1.88, 2.20]
	0.75	0.00	1	0.00	1.00	[0.90, 1.10]
	0.30	0.00	1	0.00	1.55	[1.33, 1.77]
	0.05	0.00	1	0.00	1.36	[1.18, 1.54]
	0.16	0.00	1	0.00	2.49	[2.04, 2.94]
	0.16	0.00	1	0.00	0.72	[0.62, 0.82]
	0.75	0.00	1	0.00	1.17	[1.03, 1.31]
	1.10	0.00	1	0.00	0.97	[0.70, 1.24]
	0.50	0.00	8	0.90	3.62	[3.21, 4.03]
Pijlman et al., 2020	0.79	0.00	2	0.43	2.41	[2.12, 2.70]
	0.80	0.00	2	0.36	2.40	[2.01, 2.79]
	0.81	0.00	2	0.23	2.26	[1.81, 2.71]
	0.81	0.00	1	0.00	1.84	[1.66, 2.02]
Savage et al., 2019	0.58	0.00	5	0.72	1.09	[0.85, 1.34]
	0.59	0.22	12	0.82	3.50	[3.02, 3.98]
	0.57	0.21	18	0.88	4.10	[3.52, 4.68]
Nobilly et al., 2013	0.76	0.40	2	0.48	15.15	[15.06, 15.24]
	0.82	0.39	5	0.70	16.77	[16.65, 16.89]
Minnee et al., 2013	0.81	0.00	1	0.00	0.02	[−2.50, 2.54]
	0.92	0.48	2	0.50	0.02	[−2.33, 2.36]
	0.75	0.00	1	0.00	0.02	[−2.60, 2.63]
Daly et al., 1996	0.70	0.22	2	0.34	13.49	[11.70, 15.28]
	0.71	0.26	16	0.86	18.49	[16.70, 20.28]
	0.88	0.27	10	0.83	17.89	[16.17, 19.61]
	0.88	0.33	9	0.79	18.98	[17.17, 20.79]
	0.70	0.22	2	0.34	21.39	[19.28, 23.50]
	0.71	0.26	16	0.86	26.45	[23.93, 28.97]
	0.88	0.27	10	0.83	26.33	[23.81, 28.85]
	0.88	0.33	9	0.79	26.69	[24.35, 29.03]
Ruz−Jerez et al., 1991	0.66	0.30	2	0.42	11.69	[9.34, 14.03]
	0.40	0.36	22	0.91	15.23	[12.71, 17.75]
	0.81	0.00	1	0.00	16.97	[14.50, 19.45]
Totty et al., 2013	0.71	0.20	2	0.32	2.52	[2.30, 2.75]
	0.63	0.36	2	0.46	2.52	[2.29, 2.75]
	0.96	0.10	5	0.68	2.73	[2.50, 2.95]
Moorhead & Piggot, 2009	0.68	0.30	3	0.46	13.20	[11.09, 15.31]
	0.70	0.17	4	0.51	16.30	[14.05, 18.55]
	0.70	0.25	3	0.41	13.50	[11.45, 15.55]
	0.69	0.20	4	0.59	15.70	[13.72, 17.68]
	0.70	0.27	3	0.42	16.70	[14.31, 19.09]
	0.67	0.24	4	0.57	21.40	[19.20, 23.60]
	0.76	0.13	3	0.23	13.40	[10.97, 15.83]
	0.71	0.16	4	0.60	17.40	[15.10, 19.70]
	0.74	0.17	3	0.29	17.10	[14.81, 19.39]
	0.71	0.17	4	0.62	18.50	[16.20, 20.80]
	0.72	0.22	3	0.37	13.00	[10.70, 15.30]
	0.67	0.24	4	0.56	17.60	[15.31, 19.89]
Powell et al., 2007	0.75	0.00	1	0.00	5.22	[2.24, 8.20]
	1.27	0.00	1	0.00	3.03	[0.05, 6.01]
	0.53	1.00	1	0.00	2.94	[−0.04, 5.92]
Rollo et al., 1998	1.27	0.00	1	0.00	9.05	[8.19, 9.91]
	0.81	0.00	1	0.00	9.86	[8.99, 10.73]
	1.50	0.00	1	0.00	10.43	[9.68, 11.18]
	1.27	0.00	1	0.00	9.59	[8.61, 10.57]
Hunter et al., 1994	0.86	1.00	1	0.00	11.72	[10.06, 13.38]
	0.30	1.00	1	0.00	5.76	[4.29, 7.23]
	0.53	1.00	1	0.00	4.76	[3.26, 6.26]
	0.75	0.00	1	0.00	7.24	[5.77, 8.71]
	1.27	0.00	1	0.00	6.96	[5.76, 8.16]
	0.86	1.00	1	0.00	7.54	[5.06, 10.02]
Brown et al., 2003	1.27	0.00	1	0.00	13.73	[13.05, 14.41]
	0.86	1.00	1	0.00	19.84	[19.16, 20.52]
	0.53	1.00	1	0.00	13.21	[12.53, 13.89]
Brown et al., 2000	1.27	0.00	1	0.00	18.10	[16.51, 19.69]
	0.86	1.00	1	0.00	25.10	[23.51, 26.69]
	0.53	1.00	1	0.00	18.45	[16.86, 20.04]
Hutton et al., 2011	0.79	0.05	2	0.09	3.12	[2.39, 3.85]
	0.86	0.29	4	0.71	2.34	[1.61, 3.07]
Judson, 2008	0.15	0.00	1	0.00	1.60	[1.51, 1.69]
	0.81	0.00	1	0.00	1.50	[1.40, 1.60]
	0.75	0.00	1	0.00	1.00	[0.93, 1.07]
Judson et al., 2009	0.81	0.00	1	0.00	1.10	[0.82, 1.38]
	0.75	0.00	1	0.00	0.95	[0.74, 1.16]
	0.81	0.00	1	0.00	2.10	[1.84, 2.36]
	0.75	0.00	1	0.00	0.60	[0.36, 0.84]
Moorhead et al., 2002	0.81	0.00	1	0.00	3.10	[2.67, 3.53]
	0.75	0.00	1	0.00	2.02	[1.77, 2.27]
Wills et al., 1987	0.86	1.00	1	0.00	2.00	[1.89, 2.10]
	0.78	0.28	2	0.41	1.49	[1.36, 1.62]
	0.99	0.07	2	0.14	1.04	[0.95, 1.12]
	1.37	0.21	2	0.33	0.97	[0.85, 1.09]
	0.75	0.28	2	0.41	1.42	[1.36, 1.48]
	1.34	0.25	2	0.39	1.40	[1.34, 1.46]
	0.86	1.00	1	0.00	1.24	[1.14, 1.34]
Allen et al., 1975	0.49	0.63	2	0.47	10.55	[9.84, 11.26]
	0.65	0.58	2	0.49	10.11	[9.31, 10.91]
	0.60	0.39	2	0.47	6.44	[5.78, 7.10]
	0.49	0.64	2	0.46	7.17	[6.54, 7.80]
	0.57	0.61	3	0.66	10.94	[10.08, 11.80]
	0.53	0.54	3	0.61	10.64	[9.78, 11.50]
	0.63	0.50	3	0.61	9.49	[8.85, 10.13]
	0.58	0.56	4	0.69	10.74	[10.00, 11.48]
	0.81	0.00	1	0.00	6.51	[5.73, 7.29]
	0.86	1.00	1	0.00	1.41	[0.32, 2.50]
	0.49	0.63	2	0.47	5.03	[3.69, 6.37]
	0.65	0.58	2	0.49	5.97	[4.62, 7.32]
	0.60	0.39	2	0.47	4.31	[2.99, 5.63]
	0.49	0.64	2	0.46	4.25	[3.12, 5.38]
	0.57	0.61	3	0.66	5.57	[4.10, 7.04]
	0.53	0.54	3	0.61	5.07	[3.74, 6.40]
	0.63	0.50	3	0.61	5.36	[4.14, 6.58]
	0.58	0.56	4	0.69	5.50	[4.25, 6.75]
	0.81	0.00	1	0.00	2.23	[0.96, 3.50]
	0.86	1.00	1	0.00	4.54	[2.98, 6.10]
	0.54	0.53	2	0.50	2.91	[1.99, 3.83]
	0.69	0.45	2	0.50	1.97	[0.96, 2.98]
	0.66	0.27	2	0.40	1.54	[0.47, 2.61]
	0.54	0.55	2	0.50	2.49	[1.57, 3.41]
	0.61	0.49	3	0.62	2.76	[1.71, 3.81]
	0.59	0.43	3	0.56	2.92	[1.98, 3.86]
	0.67	0.38	3	0.53	1.58	[0.59, 2.57]
	0.62	0.43	4	0.61	3.02	[1.82, 4.22]
	0.81	0.00	1	0.00	1.22	[0.33, 2.11]
Kenyon et al., 2010	0.81	0.02	2	0.03	3.19	[2.53, 3.85]
	0.76	0.00	3	0.34	4.75	[4.14, 5.35]
	0.81	0.03	4	0.30	5.07	[4.46, 5.67]
Hume et al., 1995	0.69	0.28	3	0.47	13.77	[13.31, 14.23]
	0.68	0.17	4	0.58	12.81	[12.34, 13.28]
	1.18	0.26	3	0.45	14.18	[13.81, 14.55]
	0.76	0.37	3	0.54	14.87	[14.44, 15.30]
	0.63	0.45	3	0.60	13.36	[12.97, 13.75]
Cullen, 1965	0.69	0.62	4	0.67	11.54	[10.35, 12.74]
	0.54	0.72	4	0.68	10.55	[9.18, 11.93]
	0.62	0.83	4	0.65	11.84	[10.61, 13.06]
	0.71	0.79	4	0.66	11.99	[10.91, 13.06]
	0.55	0.67	5	0.71	11.99	[10.86, 13.12]
	0.78	0.68	4	0.68	11.38	[10.24, 12.51]
	0.92	0.72	4	0.68	12.92	[11.55, 14.28]
	0.86	1.00	1	0.00	10.02	[8.99, 11.05]
Thomson, 1977	0.66	0.30	2	0.42	13.04	[12.04, 14.04]
	0.86	1.00	1	0.00	20.12	[18.91, 21.33]
Marley et al., 1995	0.86	1.00	1	0.00	1.12	[0.86, 1.38]
	0.53	1.00	1	0.00	1.32	[1.04, 1.60]
	0.30	1.00	1	0.00	1.37	[1.03, 1.71]
	0.81	0.00	1	0.00	0.94	[0.78, 1.10]
Wilman & Asiedu, 1983	0.53	1.00	1	0.00	0.95	[0.88, 1.02]
	0.86	1.00	1	0.00	1.81	[1.75, 1.88]
	1.50	1.00	1	0.00	0.65	[0.58, 0.71]
	0.81	0.00	1	0.00	2.32	[2.26, 2.39]
Davies et al., 1953	0.86	1.00	1	0.00	15.55	[13.48, 17.62]
	0.73	0.72	4	0.62	14.35	[12.28, 16.42]
	0.86	0.90	2	0.18	16.19	[14.12, 18.26]
	0.82	0.72	2	0.40	15.45	[13.38, 17.52]
	0.73	1.00	2	0.36	14.07	[12.00, 16.14]
	0.55	0.65	4	0.69	15.02	[12.95, 17.09]
	0.53	1.00	1	0.00	14.70	[12.63, 16.77]
	0.73	0.00	2	0.35	8.34	[6.27, 10.41]
Ellis−Davies & Tyler, 1962	0.86	1.00	1	0.00	12.15	[10.14, 14.16]
	0.77	0.83	2	0.28	12.86	[10.89, 14.83]
	0.80	0.91	2	0.17	11.10	[9.24, 12.96]
	0.82	0.72	2	0.40	10.86	[8.80, 12.92]
	0.86	1.00	1	0.00	10.04	[8.47, 11.61]
	0.77	0.83	2	0.28	10.48	[8.65, 12.31]
	0.80	0.91	2	0.17	9.07	[7.24, 10.90]
	0.82	0.72	2	0.40	9.17	[7.48, 10.86]
McLean et al., 1962	0.86	1.00	1	0.00	14.30	[12.33, 16.27]
	0.30	1.00	1	0.00	7.12	[5.52, 8.72]
	0.16	0.00	1	0.00	6.12	[4.55, 7.69]
	0.15	0.00	1	0.00	4.30	[2.95, 5.65]
	0.81	0.00	1	0.00	6.52	[5.15, 7.89]
Ellis−Davies et al., 1960	0.86	1.00	1	0.00	8.63	[8.12, 9.14]
	0.86	1.00	1	0.00	7.04	[6.52, 7.56]
	0.86	0.90	2	0.18	8.85	[8.30, 9.40]
	0.63	0.67	2	0.44	8.72	[8.20, 9.24]
	0.80	0.88	2	0.21	9.21	[8.68, 9.74]
	0.86	0.90	2	0.18	7.49	[6.85, 8.13]
	0.63	0.67	2	0.44	7.62	[7.11, 8.13]
	0.80	0.88	2	0.21	7.78	[7.27, 8.29]
	0.58	0.85	2	0.26	6.75	[6.35, 7.15]
	0.36	0.55	2	0.49	7.89	[7.40, 8.38]
	0.49	0.82	2	0.29	7.75	[7.24, 8.26]
	0.81	0.00	1	0.00	4.15	[3.71, 4.59]
	0.16	0.00	1	0.00	4.66	[4.15, 5.17]
	0.30	0.00	1	0.00	5.11	[4.54, 5.68]

Citation	Root depth	Leaf nitrogen	Species richness	Species evenness	Sheep DLWG	CI
Douglas, 1995	0.30	33.72	1	0.00	275.00	[255.01, 294.99]
	0.86	41.15	1	0.00	263.00	[243.01, 282.99]
	0.69	38.86	2	0.64	260.00	[240.01, 279.99]
	0.30	33.72	1	0.00	228.00	[211.93, 244.07]
	0.86	41.15	1	0.00	183.00	[166.93, 199.07]
	0.77	39.97	2	0.34	186.00	[169.93, 202.07]
Fraser & Rowarth, 1996	0.81	25.70	1	0.00	120.68	[115.73, 125.63]
	0.30	37.83	1	0.00	224.58	[218.75, 230.41]
	1.27	32.77	1	0.00	191.24	[183.94, 198.55]
	0.75	19.74	1	0.00	105.65	[100.28, 111.02]
	0.30	33.72	1	0.00	185.28	[177.74, 192.82]
Hutton et al., 2011	0.79	26.28	2	0.09	204.92	[203.15, 206.69]
	0.86	30.80	4	0.71	253.43	[251.87, 254.98]
Komolong, 1994	1.27	32.77	1	0.00	272.70	[225.03, 320.37]
	0.71	25.10	1	0.00	204.80	[185.40, 224.20]
Judson, 2008	0.15	26.68	1	0.00	332.00	[320.21, 343.79]
	0.81	25.70	1	0.00	270.00	[258.93, 281.07]
	0.75	19.74	1	0.00	370.00	[358.95, 381.05]
Judson et al., 2009	0.81	25.70	1	0.00	296.00	[284.51, 307.49]
	0.75	19.74	1	0.00	376.00	[367.74, 384.26]
	0.81	25.70	1	0.00	309.00	[296.76, 321.24]
	0.75	19.74	1	0.00	346.00	[337.18, 354.82]
Moorhead et al., 2002	0.81	25.70	1	0.00	135.00	[131.28, 138.72]
	0.75	19.74	1	0.00	222.00	[212.20, 231.80]
Purchas & Keogh, 1984	0.30	31.57	1	0.00	163.00	[144.17, 181.83]
	0.30	37.83	1	0.00	215.00	[191.87, 238.13]
	0.30	31.57	1	0.00	193.00	[155.13, 230.87]
	0.30	37.83	1	0.00	225.00	[190.48, 259.52]
	0.30	31.57	1	0.00	219.00	[201.37, 236.63]
	0.30	37.83	1	0.00	217.00	[195.17, 238.83]
	0.30	31.57	1	0.00	217.00	[201.67, 232.33]
	0.30	37.83	1	0.00	236.00	[212.27, 259.73]
	0.30	31.57	1	0.00	168.00	[151.80, 184.20]
	0.30	37.83	1	0.00	203.00	[182.95, 223.05]
Robertson et al., 1995	0.30	31.57	1	0.00	232.10	[215.97, 248.23]
	0.30	31.57	1	0.00	160.30	[141.37, 179.23]
	0.75	19.74	1	0.00	51.20	[35.07, 67.33]
	0.75	19.74	1	0.00	−2.40	[−21.33, 16.53]
	0.86	41.15	1	0.00	243.40	[227.27, 259.53]
	0.86	41.15	1	0.00	121.40	[102.47, 140.33]
	0.30	33.72	1	0.00	207.70	[191.57, 223.83]
	0.30	33.72	1	0.00	85.70	[66.77, 104.63]
	0.66	29.28	2	0.42	165.50	[149.37, 181.63]
	0.66	29.28	2	0.42	88.40	[69.47, 107.33]
Wang et al., 1994	0.30	33.72	1	0.00	203.00	[191.63, 214.37]
	0.30	33.72	1	0.00	188.00	[176.63, 199.37]
	0.86	41.15	1	0.00	185.00	[173.63, 196.37]
	0.86	41.15	1	0.00	178.00	[166.63, 189.37]
Min et al., 2001	0.30	33.72	1	0.00	16.30	[2.82, 29.78]
	0.30	33.72	1	0.00	22.30	[8.82, 35.78]
	0.66	29.28	2	0.42	43.20	[29.72, 56.68]
Fraser et al., 2004	0.86	41.15	1	0.00	243.00	[207.91, 278.09]
	0.53	41.90	1	0.00	305.00	[262.99, 347.01]
	0.81	25.70	1	0.00	184.00	[153.85, 214.15]
Golding et al., 2008	0.99	28.42	4	0.58	247.00	[233.28, 260.72]
	0.77	22.80	3	0.52	107.00	[93.28, 120.72]
	0.80	25.98	2	0.05	119.00	[105.28, 132.72]
Kenyon et al., 2010	0.81	25.89	2	0.03	242.34	[240.10, 244.58]
	0.76	21.08	3	0.34	249.82	[247.80, 251.84]
	0.81	22.30	4	0.30	238.12	[236.15, 240.10]
Marley et al., 2003	1.27	32.77	1	0.00	148.00	[100.96, 195.04]
	0.30	33.72	1	0.00	124.00	[80.88, 167.12]
	0.66	29.28	2	0.42	129.00	[83.92, 174.08]
Scales et al., 1994	0.81	25.70	1	0.00	120.90	[101.56, 140.23]
	0.81	25.70	1	0.00	114.93	[96.67, 133.18]
	0.71	25.10	1	0.00	131.34	[113.18, 149.51]
	0.71	25.10	1	0.00	125.37	[106.16, 144.59]
	1.50	20.18	1	0.00	125.37	[109.98, 140.77]
	1.50	20.18	1	0.00	119.40	[101.90, 136.90]
	1.27	32.77	1	0.00	208.96	[184.85, 233.06]
	1.27	32.77	1	0.00	202.99	[182.44, 223.53]
	0.86	41.15	1	0.00	161.19	[140.20, 182.19]
	0.86	41.15	1	0.00	155.22	[131.95, 178.50]
	0.81	25.70	1	0.00	131.68	[114.22, 149.15]
	0.81	25.70	1	0.00	105.94	[93.02, 118.86]
	0.71	25.10	1	0.00	110.89	[98.06, 123.72]
	0.71	25.10	1	0.00	85.15	[71.34, 98.95]
	1.50	20.18	1	0.00	123.76	[108.87, 138.65]
	1.50	20.18	1	0.00	98.02	[83.13, 112.91]
	1.27	32.77	1	0.00	197.03	[177.92, 216.14]
	1.27	32.77	1	0.00	171.29	[152.73, 189.85]
	0.86	41.15	1	0.00	192.08	[172.82, 211.33]
	0.86	41.15	1	0.00	166.34	[144.10, 188.57]
Speijers et al., 2004	0.30	33.72	1	0.00	278.00	[251.49, 304.51]
	0.86	41.15	1	0.00	200.00	[156.78, 243.22]
	0.53	41.90	1	0.00	228.00	[182.94, 273.06]
	0.81	25.70	1	0.00	182.00	[152.18, 211.82]
Athanasiadou et al., 2007	0.66	29.28	2	0.42	219.00	[183.76, 254.24]
	0.66	29.28	2	0.42	269.00	[231.98, 306.02]
	1.27	32.77	1	0.00	262.00	[217.37, 306.63]
	1.27	32.77	1	0.00	268.00	[216.88, 319.12]
Niezen et al., 1993	0.81	25.70	1	0.00	33.30	[11.74, 54.86]
	0.81	25.70	1	0.00	62.20	[40.64, 83.76]
	0.30	31.57	1	0.00	184.30	[162.74, 205.86]
	0.30	31.57	1	0.00	195.30	[173.74, 216.86]
	0.86	41.15	1	0.00	215.00	[146.01, 283.99]
	0.86	41.15	1	0.00	220.00	[151.01, 288.99]
	0.86	41.15	1	0.00	244.50	[201.77, 287.23]
	0.86	41.15	1	0.00	50.00	[7.27, 92.73]
Niezen et al., 1994	0.30	31.57	1	0.00	285.70	[257.67, 313.73]
	0.30	31.57	1	0.00	285.70	[257.67, 313.73]
	1.27	32.77	1	0.00	166.70	[138.67, 194.73]
	1.27	32.77	1	0.00	168.20	[140.17, 196.23]
	0.53	41.90	1	0.00	178.60	[150.57, 206.63]
	0.53	41.90	1	0.00	193.50	[165.47, 221.53]
	0.53	41.90	1	0.00	171.00	[142.97, 199.03]
	0.53	41.90	1	0.00	166.70	[138.67, 194.73]
	0.86	41.15	1	0.00	136.40	[108.37, 164.43]
	0.86	41.15	1	0.00	261.90	[233.87, 289.93]
	0.66	29.28	2	0.42	84.30	[56.27, 112.33]
	0.66	29.28	2	0.42	131.00	[102.97, 159.03]
Niezen et al., 1995	0.86	41.15	1	0.00	184.00	[146.96, 221.04]
	0.86	41.15	1	0.00	−39.00	[−76.04, −1.96]
Min et al., 1999	0.66	29.28	2	0.42	4.50	[−8.98, 17.98]
	0.66	29.28	2	0.42	18.60	[5.12, 32.08]
	0.30	33.72	1	0.00	33.80	[20.32, 47.28]
	0.30	33.72	1	0.00	40.30	[26.82, 53.78]
Wang et al., 1996	0.30	33.72	1	0.00	203.00	[191.63, 214.37]
	0.30	33.72	1	0.00	188.00	[176.63, 199.37]
	0.86	41.15	1	0.00	185.00	[173.63, 196.37]
	0.86	41.15	1	0.00	178.00	[166.63, 189.37]
Thomson, 1977	0.66	29.28	2	0.42	277.38	[269.50, 285.27]
	0.86	41.15	1	0.00	264.29	[255.29, 273.28]
Jagusch et al., 1981	0.53	41.90	1	0.00	220.00	[194.52, 245.48]
	0.30	37.83	1	0.00	256.00	[230.52, 281.48]
	0.66	29.28	2	0.42	207.00	[181.52, 232.48]
	0.86	41.15	1	0.00	177.00	[153.48, 200.52]
	0.53	41.90	1	0.00	183.00	[149.68, 216.32]
	0.30	37.83	1	0.00	209.00	[173.72, 244.28]
	0.66	29.28	2	0.42	128.00	[98.60, 157.40]
	0.86	41.15	1	0.00	178.00	[146.64, 209.36]
Marley et al., 1995	0.86	41.15	1	0.00	227.60	[184.22, 270.98]
	0.86	41.15	1	0.00	191.60	[151.54, 231.66]
	0.53	41.90	1	0.00	309.80	[266.74, 352.86]
	0.53	41.90	1	0.00	273.80	[234.21, 313.39]
	0.30	37.83	1	0.00	300.30	[264.39, 336.21]
	0.30	37.83	1	0.00	264.30	[231.71, 296.89]
	0.81	25.70	1	0.00	218.70	[188.08, 249.32]
	0.81	25.70	1	0.00	182.70	[152.75, 212.65]
Rattray et al., 1976	0.66	29.28	2	0.42	240.50	[227.96, 253.04]
	0.86	41.15	1	0.00	263.10	[241.60, 284.60]
Niezen et al., 1998	0.30	33.72	1	0.00	207.70	[191.57, 223.83]
	0.30	33.72	1	0.00	85.70	[66.77, 104.63]
	0.86	41.15	1	0.00	243.40	[227.27, 259.53]
	0.86	41.15	1	0.00	121.40	[102.47, 140.33]
	0.30	31.57	1	0.00	232.10	[215.97, 248.23]
	0.30	31.57	1	0.00	160.30	[141.37, 179.23]
	0.75	19.74	1	0.00	51.20	[35.07, 67.33]
	0.75	19.74	1	0.00	−2.40	[−21.33, 16.53]
	0.66	29.28	2	0.42	165.50	[149.37, 181.63]
	0.66	29.28	2	0.42	88.40	[69.47, 107.33]
Nicol & McLean, 1970	0.81	25.70	1	0.00	210.00	[186.48, 233.52]
	0.86	41.15	1	0.00	370.00	[346.48, 393.52]
Barry, 1985	0.30	31.57	1	0.00	27.00	[3.82, 50.18]
	0.30	31.57	1	0.00	70.00	[48.76, 91.24]
McLean et al., 1962	0.86	41.15	1	0.00	252.00	[222.46, 281.54]
	0.30	37.83	1	0.00	271.00	[249.98, 292.02]
	0.16	25.43	1	0.00	170.00	[150.17, 189.83]
	0.15	26.68	1	0.00	147.00	[125.26, 168.74]
	0.81	25.70	1	0.00	105.00	[84.60, 125.40]
	0.86	41.15	1	0.00	79.40	[57.98, 100.82]
	0.30	37.83	1	0.00	155.00	[139.49, 170.51]
	0.16	25.43	1	0.00	124.00	[105.52, 142.48]
	0.15	26.68	1	0.00	167.00	[151.31, 182.69]
	0.81	25.70	1	0.00	127.00	[110.81, 143.19]
Leathwick & Atkinson, 1996	0.30	33.72	1	0.00	160.00	[151.45, 168.55]
	0.66	29.28	2	0.42	73.00	[59.63, 86.37]
Jagusch et al., 1979	0.86	41.15	1	0.00	196.30	[155.53, 237.07]
	0.74	27.52	2	0.26	185.00	[156.73, 213.27]
	0.81	25.70	1	0.00	133.50	[105.81, 161.19]
	0.30	37.83	1	0.00	201.40	[171.92, 230.88]
	0.53	41.90	1	0.00	179.80	[140.19, 219.41]
	0.74	27.52	2	0.26	133.90	[101.58, 166.22]
	0.86	41.15	1	0.00	133.90	[93.03, 174.77]
Hight et al., 1972	0.30	37.83	1	0.00	118.00	[108.28, 127.72]
	0.86	41.15	1	0.00	132.00	[120.32, 143.68]
	0.66	29.28	2	0.42	71.70	[58.06, 85.34]
	0.30	37.83	1	0.00	168.00	[140.36, 195.64]
	0.86	41.15	1	0.00	136.00	[106.40, 165.60]
	0.66	29.28	2	0.42	113.00	[81.44, 144.56]
Grace et al., 2019	0.81	25.70	1	0.00	268.00	[254.28, 281.72]
	0.67	29.23	2	0.41	278.00	[264.28, 291.72]
	0.38	28.32	6	0.65	281.00	[267.28, 294.72]
	0.44	28.03	9	0.79	274.00	[260.28, 287.72]

−100 −50 0 50 100 150 200 250 300 350 400



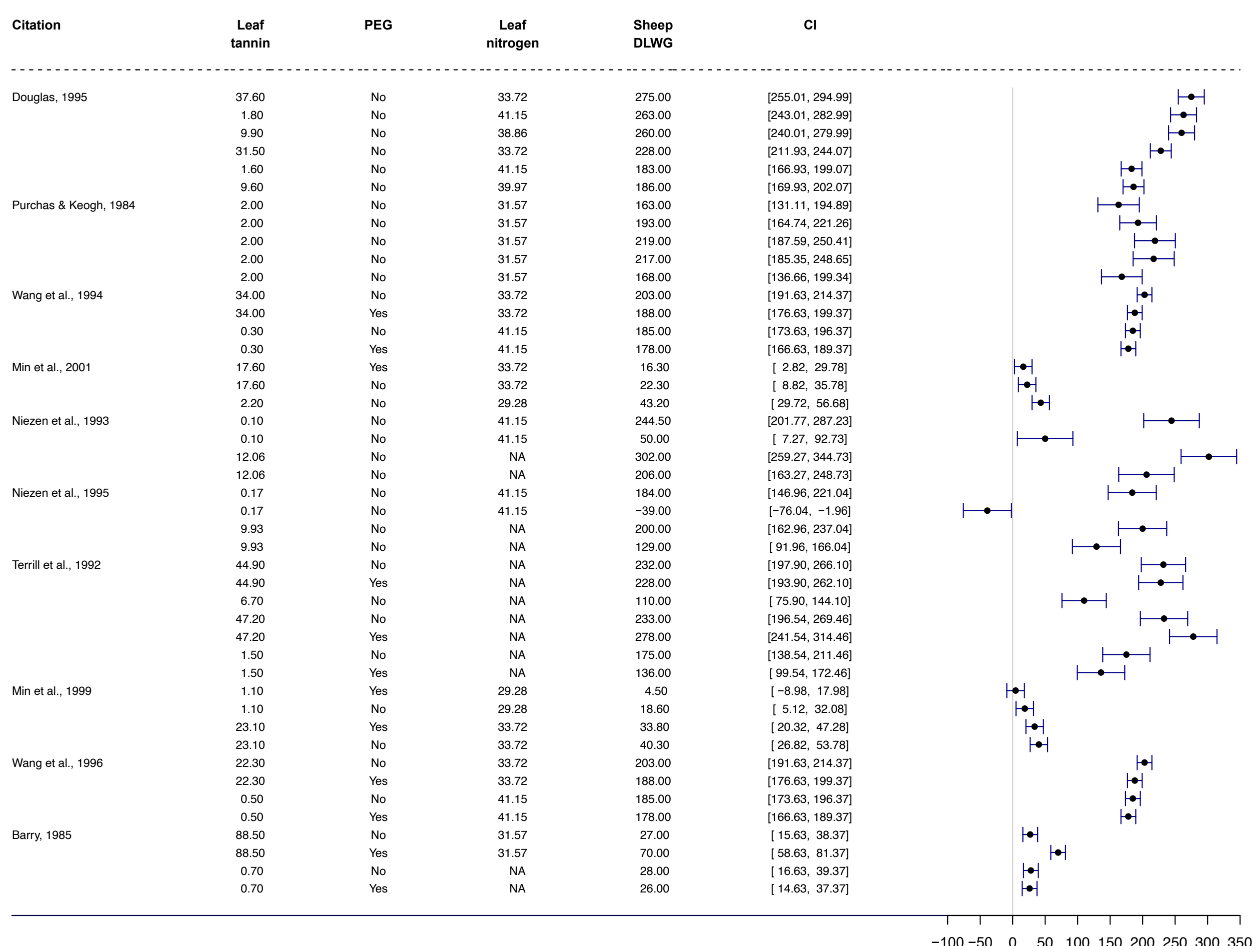
Citation	Leaf nitrogen	Wool growth	CI
Robertson et al., 1995	31.57	0.61	[0.56, 0.65]
	19.74	0.57	[0.53, 0.61]
	41.15	0.72	[0.68, 0.77]
	33.72	0.74	[0.69, 0.78]
	29.28	0.68	[0.63, 0.72]
Niezen et al., 1995	41.15	1.19	[0.95, 1.42]
Niezen et al., 1998	33.72	0.74	[0.68, 0.80]
	41.15	0.72	[0.67, 0.78]
	31.57	0.67	[0.61, 0.73]
	19.74	0.58	[0.52, 0.63]
	29.28	0.68	[0.62, 0.73]



Citation	Leaf nitrogen	Wool growth	CI
Fraser & Rowarth, 1996	25.70	15.04	[14.27, 15.80]
	37.83	21.55	[20.72, 22.39]
	32.77	19.46	[18.69, 20.23]
	19.74	15.99	[15.30, 16.69]
	33.72	20.40	[19.35, 21.44]
Wang et al., 1994	33.72	12.10	[11.34, 12.86]
	41.15	10.80	[10.04, 11.56]
Min et al., 1999	29.28	13.20	[12.57, 13.83]
	33.72	15.65	[15.02, 16.28]
Wang et al., 1996	33.72	11.50	[10.74, 12.26]
	41.15	10.50	[9.74, 11.26]
Hight et al., 1972	37.83	18.90	[17.51, 20.29]
	41.15	18.58	[17.19, 19.97]
	29.28	14.65	[13.26, 16.03]
	37.83	24.90	[22.16, 27.64]
	41.15	24.00	[21.26, 26.74]
	29.28	24.50	[21.76, 27.24]

A4.2.4.3. Tannins

Forest plot showing estimates of sheep daily liveweight gain (DLWG, g.day^{-1}) from studies of herbal leys that measured leaf condensed tannin concentration per leaf dry matter (g.kg^{-1}) of forage, identified by systematic review. Additional columns show polyethylene glycol (PEG, inhibits tannins) treatments, and leaf nitrogen content per leaf dry mass (mg.g^{-1}) of the sward weighted by the relative abundance of species present (Appendix 4.2.1) , where able to be calculated (NA otherwise). Estimates with 95% confidence intervals are given for each treatment extracted from studies in the table and plotted adjacent for each row. These include confidence intervals calculated from imputed standard errors (SEs) for analysis (see Appendix 4.2.2).



Citation	Leaf tannin	PEG	Leaf nitrogen	Sheep DLWG	CI
Douglas, 1995	37.60	No	33.72	275.00	[255.01, 294.99]
	1.80	No	41.15	263.00	[243.01, 282.99]
	9.90	No	38.86	260.00	[240.01, 279.99]
	31.50	No	33.72	228.00	[211.93, 244.07]
	1.60	No	41.15	183.00	[166.93, 199.07]
	9.60	No	39.97	186.00	[169.93, 202.07]
Purchas & Keogh, 1984	2.00	No	31.57	163.00	[131.11, 194.89]
	2.00	No	31.57	193.00	[164.74, 221.26]
	2.00	No	31.57	219.00	[187.59, 250.41]
	2.00	No	31.57	217.00	[185.35, 248.65]
	2.00	No	31.57	168.00	[136.66, 199.34]
Wang et al., 1994	34.00	No	33.72	203.00	[191.63, 214.37]
	34.00	Yes	33.72	188.00	[176.63, 199.37]
	0.30	No	41.15	185.00	[173.63, 196.37]
	0.30	Yes	41.15	178.00	[166.63, 189.37]
Min et al., 2001	17.60	Yes	33.72	16.30	[2.82, 29.78]
	17.60	No	33.72	22.30	[8.82, 35.78]
	2.20	No	29.28	43.20	[29.72, 56.68]
Niezen et al., 1993	0.10	No	41.15	244.50	[201.77, 287.23]
	0.10	No	41.15	50.00	[7.27, 92.73]
	12.06	No	NA	302.00	[259.27, 344.73]
	12.06	No	NA	206.00	[163.27, 248.73]
Niezen et al., 1995	0.17	No	41.15	184.00	[146.96, 221.04]
	0.17	No	41.15	−39.00	[−76.04, −1.96]
	9.93	No	NA	200.00	[162.96, 237.04]
	9.93	No	NA	129.00	[91.96, 166.04]
Terrill et al., 1992	44.90	No	NA	232.00	[197.90, 266.10]
	44.90	Yes	NA	228.00	[193.90, 262.10]
	6.70	No	NA	110.00	[75.90, 144.10]
	47.20	No	NA	233.00	[196.54, 269.46]
	47.20	Yes	NA	278.00	[241.54, 314.46]
	1.50	No	NA	175.00	[138.54, 211.46]
	1.50	Yes	NA	136.00	[99.54, 172.46]
Min et al., 1999	1.10	Yes	29.28	4.50	[−8.98, 17.98]
	1.10	No	29.28	18.60	[5.12, 32.08]
	23.10	Yes	33.72	33.80	[20.32, 47.28]
	23.10	No	33.72	40.30	[26.82, 53.78]
Wang et al., 1996	22.30	No	33.72	203.00	[191.63, 214.37]
	22.30	Yes	33.72	188.00	[176.63, 199.37]
	0.50	No	41.15	185.00	[173.63, 196.37]
	0.50	Yes	41.15	178.00	[166.63, 189.37]
Barry, 1985	88.50	No	31.57	27.00	[15.63, 38.37]
	88.50	Yes	31.57	70.00	[58.63, 81.37]
	0.70	No	NA	28.00	[16.63, 39.37]
	0.70	Yes	NA	26.00	[14.63, 37.37]

A4.2.5. Sensitivity analyses results

Table A4.9. Sensitivity analyses of herbage dry matter (DM, t.ha^{-1}) and sheep and cattle daily liveweight gain (DLWG, g.day^{-1}) for studies of rotational grazing. For details of sensitivity analyses, see Appendix 4.2.2. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis. Sensitivity analysis of DLWG excluding studies with low or unclear validity based on Critical Appraisal score (CA) was not possible as only four data points from two studies were scored as High Validity.

								Standard deviation parameters		R^2		Number of	
Outcome	Model	Intercept	Proportion rest period	Stocking density	Rest period*stocking density	Cattle	Latitude	Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
Herbage DM (t.ha^{-1})	WN: CA	5.72 [1.45, 10.2]	5.53 [4.16, 6.96]*	-	-	-	-	1.46 [1.31, 1.63]	4.62 [2.16, 9.99]	0.814	0.172	8	3
DLWG (g.day^{-1})	EP: all	163 [-142, 543]	-5.72 [-59.9, 52.0]	-	-	692 [183, 1230]*	-	31.3 [11.0, 74.2]	209 [66.5, 594]	0.967	0.835	19	4

Table A4.10. Sensitivity analyses of herbage dry matter (DM, t.ha^{-1}) and sheep daily liveweight gain (DLWG, g.day^{-1}) for studies of herbal leys. For details of sensitivity analyses, see Appendix 4.2.2. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis.

											Standard deviation parameters		R^2		Number of	
Outcome	Model	Intercept	Root depth	Legume	Root*legume	Leaf N	Herbage DM	Species richness	Species evenness	Latitude	Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
Herbage DM (t.ha^{-1})	EP: all	4.36 [1.52, 7.35]	0.20 [-1.46, 1.89]	1.65 [0.31, 3.12]*	-	-	-	0.23 [-0.08, 0.52]	0.03 [-2.77, 2.82]	-0.27 [-0.94, 0.39]	1.34 [1.02, 1.77]	6.22 [4.30, 9.35]	0.939	0.0963	58	14
	EI: CA	7.97 [5.18, 10.76]	0.42 [-1.29, 2.15]	1.31 [-0.06, 2.69]	1.29 [-2.63, 5.16]	-	-	0.12 [-0.06, 0.30]	2.84 [0.71, 4.93] *	-0.45 [-1.07, 0.16]	1.45 [1.16, 1.75]	6.75 [5.00, 9.21]	0.940	0.164	114	24
	EI: SMV	6.80 [4.53, 9.03]	0.89 [-0.72, 2.60]	1.82 [0.44, 3.29] *	3.11 [-0.39, 6.72]	-	-	0.54 [-0.85, 1.95]	0.64 [-5.83, 7.09]	-0.76 [-1.24, -0.27] *	1.52 [1.15, 1.99]	5.73 [4.34, 7.63]	0.928	0.379	79	28
	EI: AV‡	5.53 [2.67, 8.43]	1.87 [-0.26, 4.07]	2.39 [0.60, 4.24]*	-	-	-	-	-	-0.56 [-1.28, 0.15]	1.99 [1.50, 2.64]	6.03 [4.20, 8.65]	0.894	0.242	52	18
	EI: TSV	6.39 [4.05, 8.69]	1.82 [0.15, 3.51] *	2.52 [1.38, 3.68] *	1.72 [-2.35, 5.83]	-	-	-0.15 [-0.48, 0.18]	3.05 [0.01, 6.07] *	-0.26 [-0.78, 0.26]	1.66 [1.35, 2.06]	5.78 [4.34, 7.75]	0.893	0.116	94	27
	EI: MD	6.93 [4.78, 9.09]	1.40 [0.07, 2.75] *	2.00 [1.04, 2.98] *	2.07 [-0.95, 5.11]	-	-	0.17 [-0.62, 0.95]	2.68 [-0.58, 5.95]	-0.31 [-0.79, 0.16]	1.47 [1.22, 1.74]	5.99 [4.65, 7.76]	0.907	0.123	146	34

DLWG (g.day^{-1})	EP: all	168 [138, 196]	-49.2 [-92.3, -4.06] *	-	-	4.81 [2.54, 7.00] *	-	4.98 [-15.4, 26.5]	3.28 [-95.6, 103]	7.06 [-0.83, 15.1]	51.8 [43.5, 62.2]	67.0 [43.2, 99.1]	0.571	0.215	103	25
	WN: CA§	236 [164, 311]	-149 [-162, -135] *	-	-	1.05 [0.61, 1.52] *	-	-	-	6.10 [-9.10, 20.9]	28.8 [27.3, 30.3]	111 [66.6, 191]	0.879	0.306	26	8
	EI: SMV	187 [166, 209]	-38.1 [-68.5, -7.00]*	-	-	3.41 [1.96, 4.81] *	-	35.1 [-18.1, 88.8]	-35.6 [-230, 159]	5.71 [0.61, 10.8] *	48.3 [41.8, 55.9]	67.2 [49.9, 87.8]	0.584	0.199	161	45
	EI: AV††	186 [163, 209]	-38.4 [-69.7, -6.78] *	-	-	3.40 [1.95, 4.85] *	-	-	-	5.74 [0.63, 10.87] *	48.7 [41.9, 56.6]	69.0 [50.9, 90.8]	0.585	0.191	149	42
	EI: TSV	184 [159, 209]	-9.19 [-44.0, 26.5]	-	-	3.55 [2.03, 5.05] *	-	-139 [-372, 93.3]	258 [-191, 709]	7.04 [1.90, 12.2] *	47.2 [39.9, 56.2]	71.5 [52.1, 95.4]	0.640	0.226	122	37
	EI: MD	193 [173, 214]	-37.4 [-67.8, -6.54]*	-	-	3.19 [1.76, 4.59]*	-	-2.06 [-22.3, 18.3]	63.2 [-67.1, 192]	6.13 [1.65, 10.7]*	48.0 [41.6, 55.6]	63.4 [46.5, 83.7]	0.580	0.221	163	45

† Although marginally significant, divergent transitions when model ran so results not reliable
‡ Simplified model because struggled to converge
§ Insufficient observations to include species richness and evenness predictors
†† All observations monocultures so species richness and evenness predictors not included as constants 1 and 0 respectively.

Table A4.11. Sensitivity analyses of sheep daily liveweight gain (DLWG, g.day^{-1}) for studies of herbal leys which measured either leaf condensed tannin concentration of treatment forages or sheep internal parasite burden. For details of sensitivity analyses, see Appendix 4.2.2. 95% Credible Intervals are given in square brackets, with * denoting where these do not overlap with 0. The - symbol denotes predictors not included in that model. All continuous predictors were centred before analysis.

										Standard deviation parameters		R^2		Number of	
Outcome	Model	Intercept	Tannin	PEG	Tannin*PEG	Leaf N	Tannin*leaf N	FEC	Latitude	Within studies	Between studies	Whole model	Fixed effects	Data points	Studies
Liveweight gain (g.day-1)	EP	160 [110, 211)	1.83 [0.24, 3.58]*	-8.93 [-59.4, 40.8]	0.32 [-2.40, 3.02]				-594 [-1830, 652]	55.6 [40.4, 78.4]	71.9 [36.2, 125]	0.621	0.212	36	9
	EP	141 [50.8, 224]	2.00 [-4.63, 9.76]	-	-	6.18 [-18.1, 34.6]	0.11 [-1.97, 2.30]	-	-	60.3 [38.8, 90.7]	71.9 [14.5, 151]	0.620	0.145	25	7
	EP	148 [108, 188]						-0.03 [-0.05, -0.02]*	3.61 [-4.69, 12.1]	52.4 [40.5, 68.7]	51.5 [12.5, 102]	0.584	0.384	45	9

A4.2.6. Supplementary figures

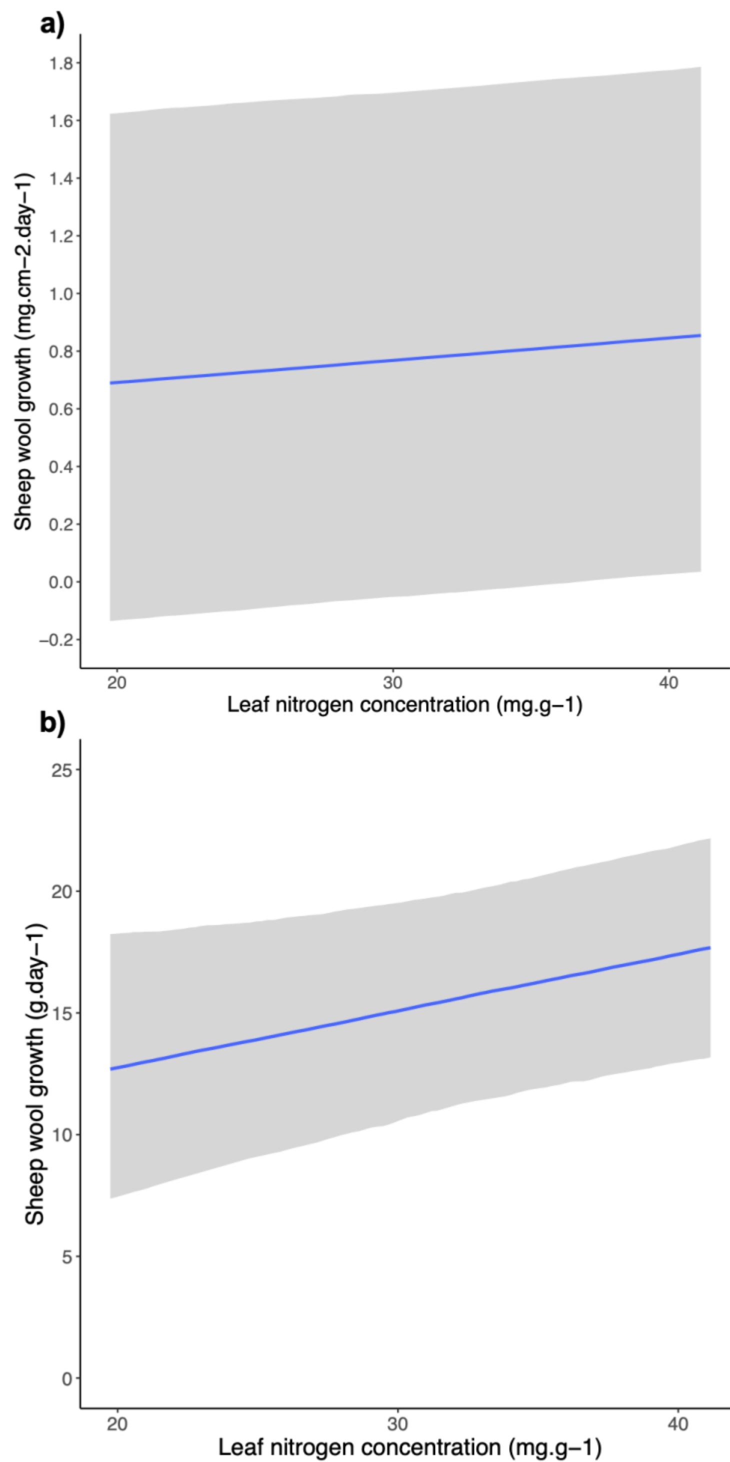


Figure A4.2. Conditional effects of leaf nitrogen concentration per leaf dry mass ($mg.g^{-1}$) on wool growth, measured by studies either in **a**] $mg.cm^{-2}.day^{-1}$, or **b**] $g.day^{-1}$. Error bars show 95% Credible Intervals. Results from EP analysis. Conditional effects show the model-fitted values for individual interventions when all other model predictors are at the reference category.

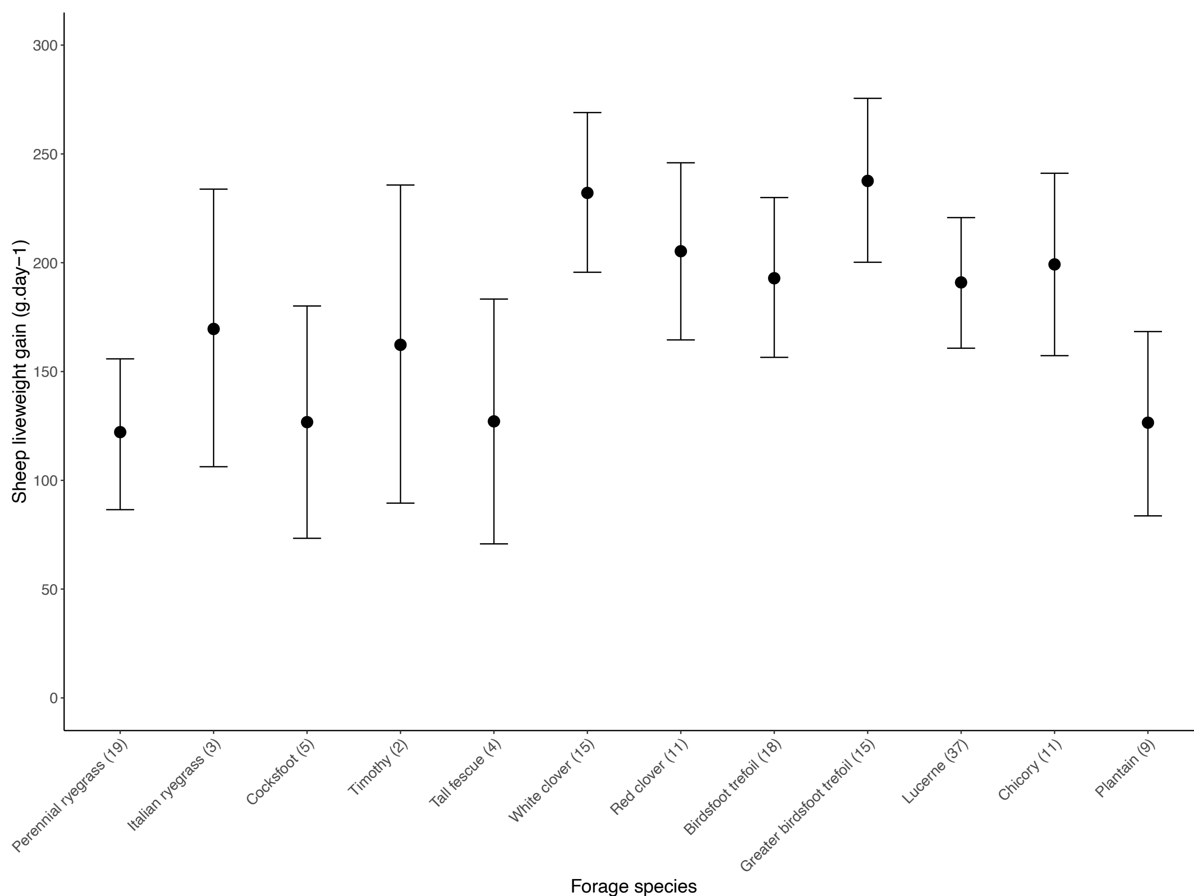
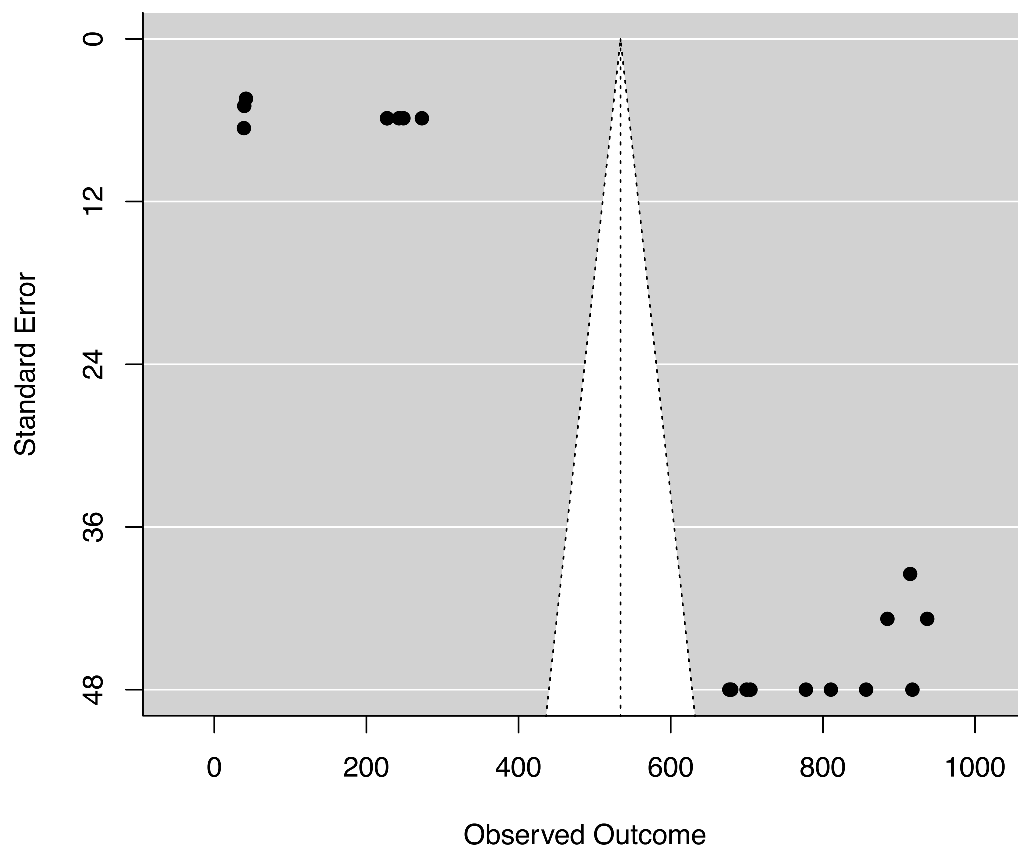


Figure A4.3. Conditional effects of forage species on sheep daily liveweight gain (g.day^{-1}). Results from AV analysis (Appendix 4.2.2), i.e. only treatments with monoculture (single species) forage included. Perennial ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiforum*), Cocksfoot (*Dactylis glomerata*), Timothy (*Phleum pratense*), Tall fescue (*Festuca arundinacea*), White clover (*Trifolium repens*) Red clover (*T. pratense*), Birdsfoot trefoil (*Lotus corniculatus*), Greater birdsfoot trefoil (*L. pedunculatus*), Lucerne (*Medicago sativa*), Chicory (*Cichorium intybus*), Plantain (*Plantago lanceolata*). Numbers in parentheses on x-axis labels indicate number of observations in dataset for each species. Error bars show 95% Credible Intervals.

A4.2.7. Funnel plot asymmetry tests

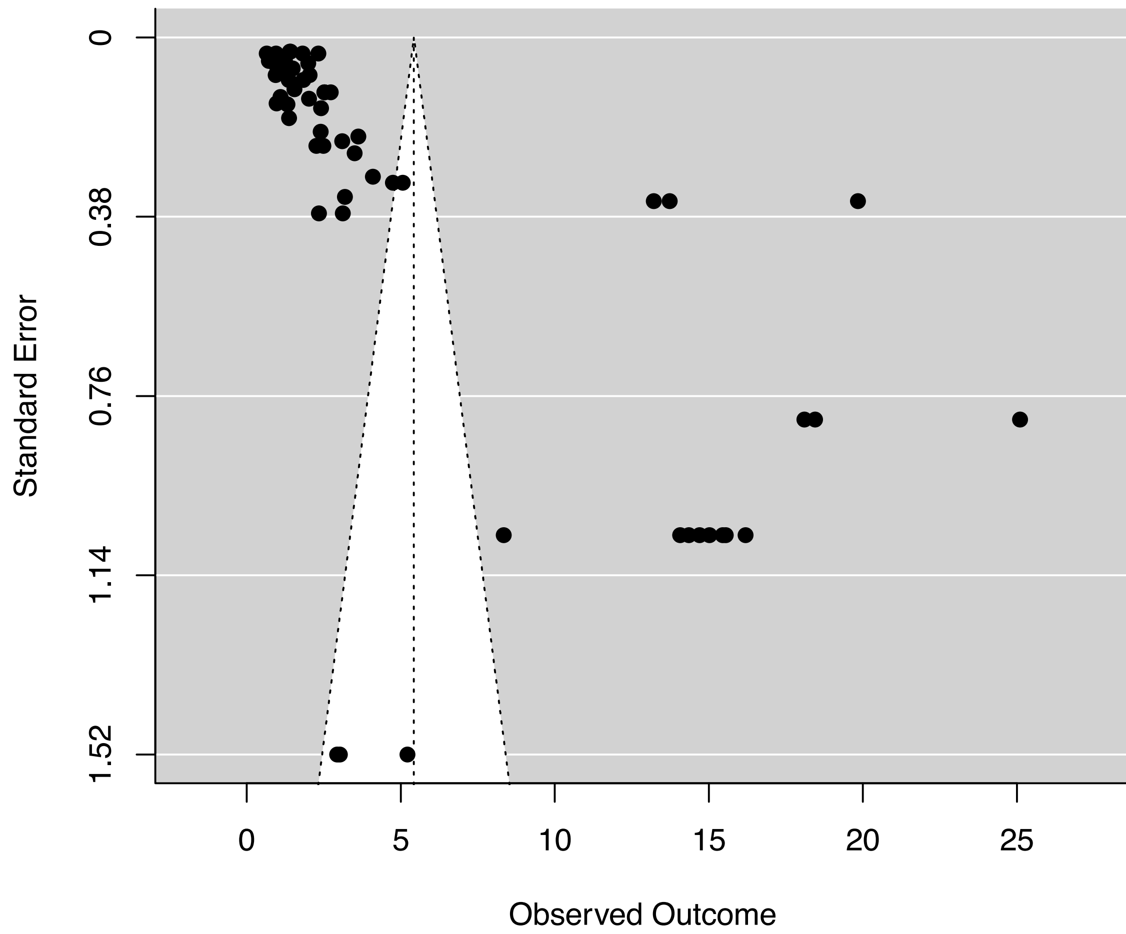
Rotational grazing - Herbage DM: Funnel plot not created because too few studies that present standard error

Rotational grazing - Livestock DLWG:



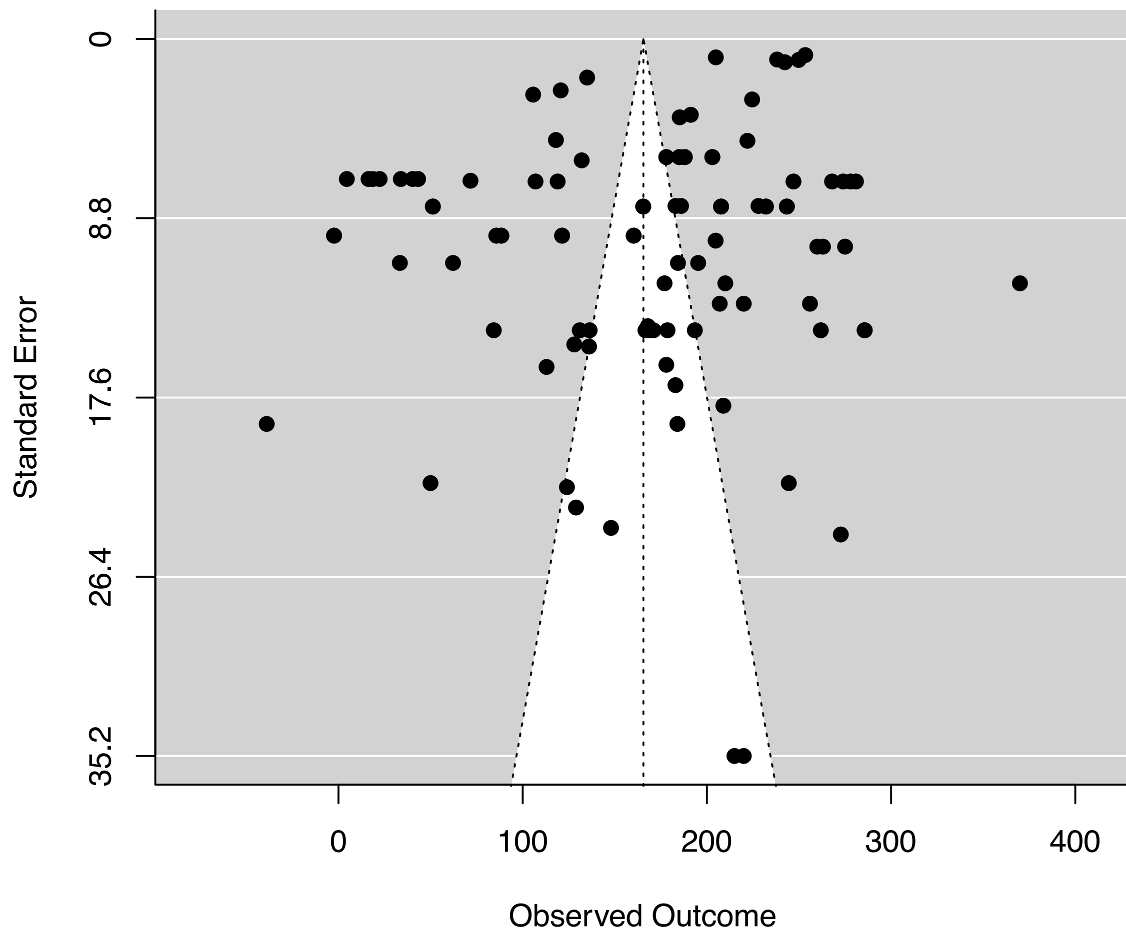
Result of regtest on rma: z = 11.0006, p < .0001

Herbal leys - Herbage DM:



Result of regtest on rma: z = 6.1274, p < .0001

Herbal leys - Livestock DLWG:



Result of regtest on rma: z = 0.1277, p = 0.8984

A4.3. References

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Appendix 5. Supplementary Materials for Chapter 7

Table A5.1. Advantages and disadvantages of adopting rotational grazing given by industry representatives and Northumberland and Devon farmers. Number of interviewees who agree (Y), disagree (N, given in brackets), or don't mention (ns) given for each reason.

		Number of interviewees									
		National		**Devon**				**Northumberland**			
		Industry rep (4)		**Adopters (3)**		**Non-adopters (1)**		**Adopters (2)**		**Non-adopters (2)**	
		Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns
Advantages	Grass productivity	3	1	2	1	(1)	0	1	1	1	1
	Grass quality	1 (1) [c]	3	0	3	0	1	0	2	0	2
	Grass recovery	1	3	2	1	0	1	1	1	1	1
	Grass utilisation	2	2	2	1	0	1	0	2	0	2
	Drought buffer	1	3	0	3	0	1	1	1	0	2
	Pasture diversity [a]	0	4	0	3	0	1	1	1	1	1
	Reduced inputs	0	4	1	2	0	1	0	2	0	2
	Livestock performance	2 (1) [d]	2	1	2	0	1	1	1	0	2
	Livestock health [b]	2	2	0	3	0	1	0	2	2	0
	Livestock contentment	0	4	2	1	0	1	1	1	0	2
	Ease of management	0	4	1	2	0	1	0	2	0	2
	Perceived best practice	0	4	1	2	1	0	1	1	0	2
	Biodiversity	0	4	1	2	0	1	0	2	0	2
Disadvantages	Infrastructure	3	1	2	1	0	1	1	1	2	0
	Labour	4	0	1	2	1	0	0	2	1	1
	Animal welfare	1 [e]	3	1	2	0	1	0	2	0	2
	Public access	1	3	0	3	0	1	0	2	0	2
	Poaching	0	4	1	2	0	1	1	1	1	1
	Incompatible with system	0	4	0	3	1	0	0	2	1	1
	No disadvantages	0	4	2	1	0	1	1	1	0	2
	Unconvinced of benefits	0	4	0	3	1	0	0	2	1	1

[a] maintains/increases pasture diversity (e.g. required to maintain herbal ley)
[b] Includes both in general and specifically reduced worm burden
[c] Risk of loss of grass quality if long rest periods in mob grazing scenarios
[d] Growth rates can be compromised if shifts too infrequent so forage quality compromised
[e] Lack of shade if grazing small paddocks in field centres, risk of mis-mothering if mix large groups of ewes and lambs together too soon after birth

Table A5.2. Advantages and disadvantages of adopting herbal leys given by industry representatives/advisors and Northumberland and Devon farmers. Number of interviewees who agree (Y), disagree (N, given in brackets), or don't mention (ns) given for each reason.

		Number of interviewees									
		National		Devon				Northumberland			
		Industry rep (4)		Adopters (3)		Non-adopters (1)		Adopters (2)		Non-adopters (2)	
		Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns
Advantages	Livestock performance [a]	1 (1)	2	3	0	1	0	2	0	1	1
	Anthelmintic properties	3	1	0	3	0	1	0	2	1	1
	Mineral/trace element availability	2	2	1	2	0	1	1	1	0	2
	Promotes rumen function	1	3	1	2	0	1	0	2	0	2
	Improved palatability	0	4	(2)	1	1	0	1 (1) [b]	1	(1)	1
	Provides grazing choice	0	4	1	2	0	1	0	2	0	2
	Improved forage production [c]	1	3	1	2	(1)	0	1 (1)	0	2 (1)	0
	Reduced fertiliser use	2	2	1	2	0	1	1	1	(1)	1
	Drought resistance	3	1	1	2	0	1	1	1	0	2
	Improved soil structure	2	2	0	3	0	1	0	2	0	2
	Increase soil organic carbon	2	2	0	3	0	1	0	2	0	2
	Good ground cover	0	4	1	2	0	1	0	2	0	2
	Biodiversity	0	4	1	2	0	1	0	2	0	2
Disadvantages	Weed control	1	3	1 (1)	1	0	1	1	1	1	1
	Expensive [d]	3	1	0	3	0	1	1	1	0	2
	Unnecessary [e]	1	3	0	3	0	1	1	1	1	1
	Poor establishment/retention [f]	2	2	3	0	0	1	2	0	1	1
	Herbs can't compete with grass	0	4	0	3	0	1	1	1	2	0
	Species not suited to land	0	4	2	1	0	1	1	1	1	1
	Reduced management flexibility [g]	3	1	1	2	0	1	1	1	(1)	1
	Requires rotational grazing	2	2	0	3	0	1	2	0	1	1
	Looks untidy	1	3	0	3	0	1	0	2	0	2
	Species difficult to eliminate	0	4	0	3	0	1	0	2	1	1

[a] includes benefit for finishing stock due to higher protein content
[b] One farmer identified improved palatability due to some components (e.g. clovers) but reduced palatability from others (e.g. chicory)
[c] Includes increased forage production stated as a benefit, but also presence of legumes fixing nitrogen which in turn benefits forage production, herbage diversity increasing production/resilience, and more consistent forage production throughout growing season (due to legumes providing late summer growth)
[d] Herbal ley seed mixes more expensive than simpler grass-clover mixes, plus reseeding costly in general
[e] Clover/grass-clover can deliver everything desired, other herbs not necessary
[f] chicory particularly prone to lack of persistence if not managed correctly

[g] Including need to remove stock for some or all of winter, and potential limitation of mating ewes on red clover

Table A5.3. Advantages and disadvantages of planting trees and hedges on farms given by industry representatives/advisors and Northumberland and Devon farmers. Number of interviewees who agree (Y), disagree (N, given in brackets), or don't mention (ns) given for each reason. All farmers interviewed in Northumberland had adopted this practice.

		Number of interviewees							
		National		Devon				Northumberland	
		Industry rep (4)		Adopters (3)		Non-adopters (1)		Adopters (4)	
		Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns
Advantages	Shelter and shade	1	3	3	0	1	0	4	0
	Good use of marginal land	3	1	0	3	1	0	1	3
	Livestock browse	1	3	1	2	0	1	1	3
	Diversified income source	1	3	1	2	0	1	2	2
	Carbon sequestration	1	3	0	3	(1)	0	2	2
	Increase soil fertility	0	4	(1)	2	0	1	1	3
	Reduce soil erosion	1	3	1	2	0	1	1	3
	Biodiversity	0	4	3	0	0	1	2	2
	Game/sport	0	4	1	2	1	0	1	3
	Cultural value [a]	0	4	2	1	0	1	1	3
	Boundary benefits [b]	1	3	2	1	0	1	2	2
Disadvantages	Sufficient shelter/trees on farm	1	3	3	0	1	0	1	3
	Inconvenience if in-field	2	2	2	1	0	1	0	4
	Loss of production under trees	2	2	1	2	0	1	0	4
	Farming more profitable	0	4	1	2	1	0	1	3
	Permanent loss of ag land	1	3	2	1	0	1	1 (1)	2
	Roots damage field drains	1	3	1	2	0	1	1	3
	Desire to focus on food production	2	2	0	3	1	0	2	2
	No grants for small-scale planting	1	3	1	2	0	1	2	2
	Grant inadequate/restrictive [c]	2	2	0	3	0	1	2	1
	Time/effort of planting	2	2	0	3	0	1	0	4
	Long time before benefit	2	2	0	3	0	1	0	4
	Vulnerability [d]	1	3	0	3	0	1	4	0
	Tree protection [e]	0	4	2	1	0	1	1	3
	Encourage flies	0	4	0	3	0	1	1	3
	Risk changed tax status	0	4	1	2	1	0	0	4
	Don't get benefits if tenant	0	4	0	3	0	1	1	3

[a] Particularly restoring historic features, e.g. hedges in Devon

[b] Includes ability to subdivide fields for RG by restoring hedges, biosecurity benefits by securing boundaries with neighbours, and ability to fence off watercourses
[c] One adopter expressed frustration at the species they were required to plant, because they felt the focus was on unproductive natives (e.g. birch, alder) rather than more valuable hardwoods (e.g. oak, beech) or softwoods
[d] Particularly to pests/diseases and storm damage, particularly because Northumberland interviews conducted week after Storm Arwen
[e] Includes frustration at plastic usage (tree guard tubes) and longevity of fences, which often use imported timber posts

Table A5.4. Advantages and disadvantages of integrating livestock and arable cropping given by industry representatives/advisors and Northumberland and Devon farmers. Number of interviewees who agree (Y), disagree (N, given in brackets), or don't mention (ns) given for each reason. 'Adopters' refer to farmers who implement mixed farming, i.e. grow some arable crops on their livestock farms. No farmers interviewed sent stock to otherwise arable-only farms seeking to integrate stock into their rotation.

		Number of interviewees									
		National		**Devon**				**Northumberland**			
		Industry rep (4)		**Adopters (2)**		**Non-adopters (2)**		**Adopters (3)**		**Non-adopters (1)**	
		Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns	Y (N)	ns
Advantages	Mixed farming										
	Improved arable soil health [a]	3	1	1	1	1	1	1	2	1	0
	Improved grassland soil health [b]	0	4	1	1	0	2	1	2	0	1
	Improved soil fertility/crop yield	4	0	1	1	1	1	1	2	1	0
	Ley reduces arable weeds	2	2	1	1	0	2	2	1	1	0
	Arable reduces grassland weeds	0	4	2	0	0	2	1	2	0	1
	Benefit of arable rotation/'rest' [c]	0	4	1	1	0	2	2	1	0	1
	Produce own cereal and straw [d]	0	4	2	0	1	1	3	0	0	1
	Reduced worm burden [e]	1	3	1	1	0	2	0	3	0	1
	Sending stock to arable										
	Low-cost outwintering [f]	0	4	0	2	2	0	0	3	1	0
	Rest own pastures	0	4	0	2	1	1	0	3	1	0
	Increase stock/enter industry	0	4	0	2	1	1	0	3	1	0
Disadvantages	Mixed farming										
	Disbenefits to following arable [g]	0	4	1	1	0	2	2	1	0	1
	Increased workload	0	4	1	1	0	2	0	3	0	1
	Capacity to store harvest on farm	0	4	1	1	0	2	0	3	0	1
	Need to reduce stock if grow crops	0	4	1	1	1	1	1	2	0	1
	Loss of income from arable crop if grow ley	1	3	0	2	0	2	0	3	0	1
	Success weather-dependent [h]	0	4	0	2	0	2	1	2	0	1
	Not cost effective [i]	0	4	0	2	1	1	1	2	0	1

Dependent on contractor	0	4	0	2	1	1	1	2	0	1
Sending stock to arable										
Lack of infrastructure [j]	2	2	0	2	2	0	2	1	1	0
Labour [k]	4	0	0	2	1	1	2	1	0	1
Proximity of arable and livestock areas	2	2	0	2	0	2	1	2	0	1
Difficult to form arable-livestock farmer partnership	2	2	0	2	0	2	0	3	1	0
Difficult with cattle	3	1	0	2	0	2	1	2	0	1
Hassle to arable farmer	3	1	0	2	0	2	1	2	1	0

[a] including increased soil organic matter and reduced runoff
[b] including the ability to aerate potentially compacted soil, bring nutrients that have leached into subsoil back to surface, opportunity to incorporate muck, and chance to reset the land if deemed 'sheep sick'
[c] including arable being a good entry for a grass ley
[d] which reduces costs and dependence on bought-in inputs, seen as improving the resilience of the farm business to the removal of existing Basic Payment Scheme farm subsidies in England
[e] sheep internal parasitic worms
[f] including reduced bought-in inputs and potentially reduced labour
[g] includes potential need to plough to terminate ley in an otherwise direct-drill system, poor corn crops because spring-sown following overwinter brassica, and increased risk of certain arable pests following grassland (e.g. leatherjackets, *Tipula spp.,* frit fly, *Oscinella frit*)
[h] including land not being difficult to harvest if conditions are wet, and can't guarantee quality straw or corn at harvest
[i] including the equipment being unaffordable, resulting in dependency on (expensive) contractors
[j] including fencing, water and handling facilities
[k] includes both lack of suitable labour in arable areas and hassle to livestock farmer of traveling to arable farm to look stock

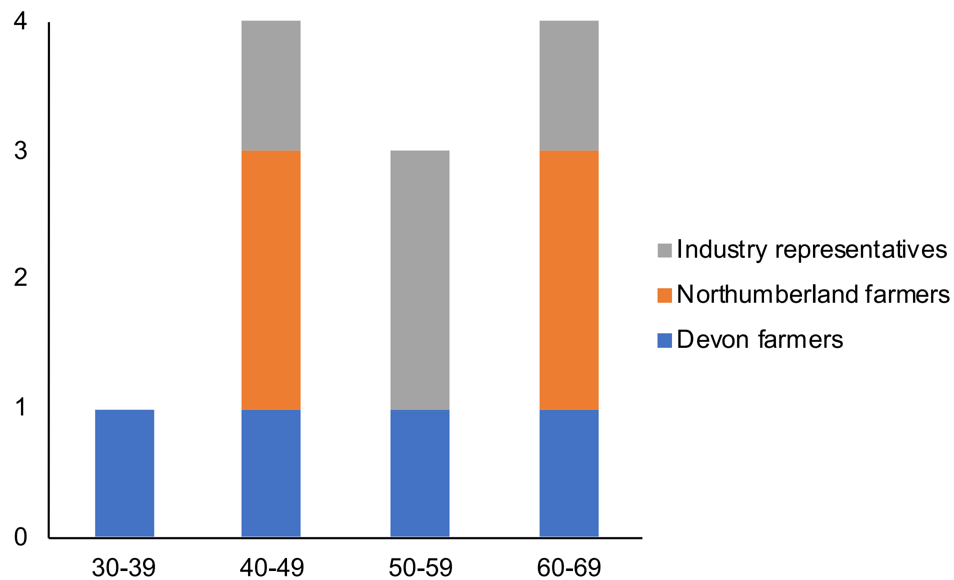

Figure A5.1. Age of participants interviewed, to the nearest 10 years.

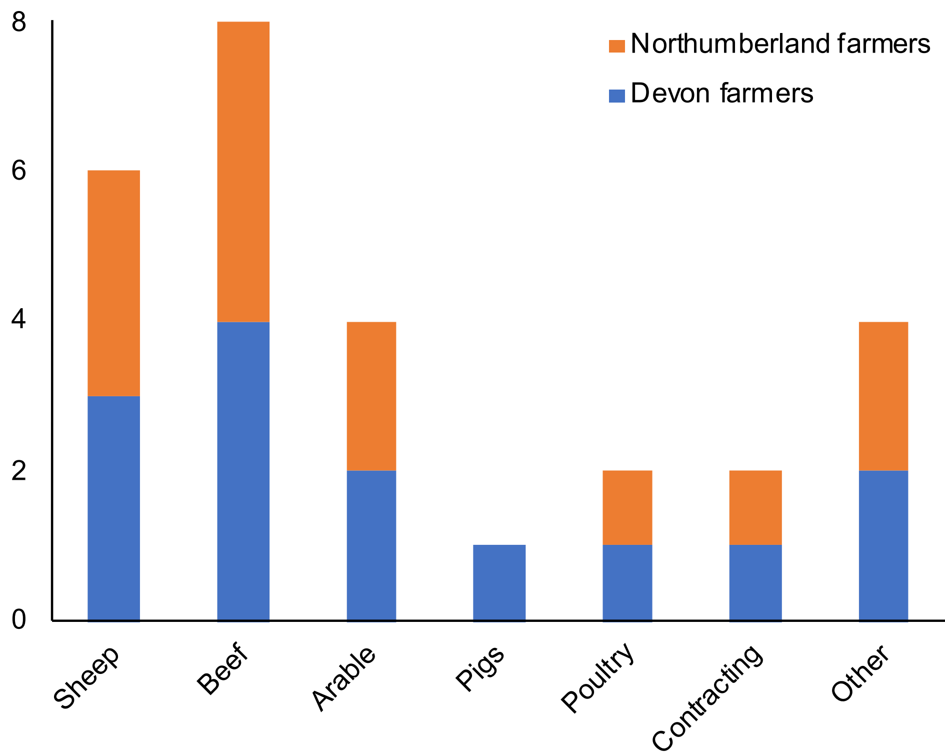

Figure A5.2. Enterprise types of farmers interviewed in Devon and Northumberland. The 'Sheep' and 'Beef' categories include both farming breeding females and buying in store animals for rearing or finishing. The 'Other' category comprised ponies, honey, alpacas and a small dairy cattle herd.

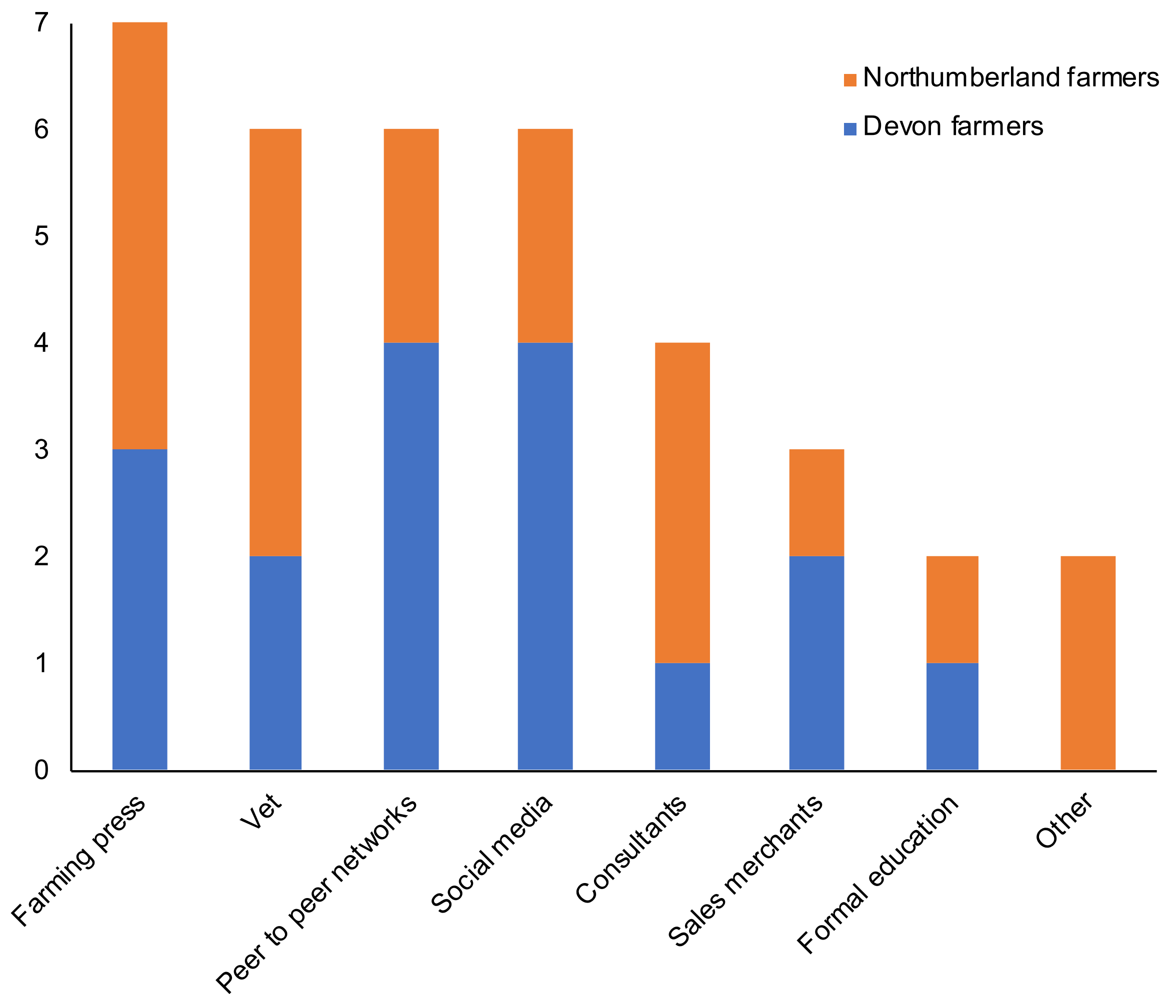

Figure A5.3. Information sources used by farmers interviewed. 'Farming press' included weekly magazines such as the *Farmers Weekly* and *Farmers Guardian*. 'Peer to peer networks' included paid membership organisations, with livestock marts and grazing groups also mentioned by some participants. 'Social media' included industry webinars in addition to mainstream platforms. 'Consultants' comprised paid farm advisors and land agents. 'Sales merchants' referred to livestock feed, fertiliser or seed salespeople. 'Formal education' refers to agricultural college or university degree courses. 'Other' comprised inputs from books and the levy board.