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TOPICAL REVIEW

What climate and environmental benefits of regenerative agriculture practices? an evidence review

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Abstract

Regenerative agriculture aims to increase soil organic carbon (SOC) levels, soil health and biodiversity. Regenerative agriculture is often juxtaposed against 'conventional' agriculture which contributes to land degradation, biodiversity loss, and greenhouse gas emissions. Although definitions of regenerative agriculture may vary, common practices include no or reduced till, cover cropping, crop rotation, reduced use or disuse of external inputs such as agrichemicals, use of farm-derived organic inputs, increased use of perennials and agroforestry, integrated crop-livestock systems, and managed grazing. While the claims associated with some of these practices are supported by more evidence than others, some studies suggest that these practices can be effective in increasing soil organic carbon levels, which can have positive effects both agriculturally and environmentally. Studies across these different regenerative agriculture practices indicate that the increase in soil organic carbon, in comparison with conventional practices, varies widely (ranging from a nonsignificant difference to as high as 3 Mg C/ha/y). Case studies from a range of regenerative agriculture systems suggest that these practices can work effectively in unison to increase SOC, but regenerative agriculture studies must also consider the importance of maintaining yield, or risk the potential of offsetting mitigation through the conversion of more land for agriculture. The carbon sequestration benefit of regenerative practices could be maximized by targeting soils that have been intensively managed and have a high carbon storage potential. The anticipated benefits of regenerative agriculture could be tested by furthering research on increasing the storage of stable carbon, rather than labile carbon, in soils to ensure its permanence.

1. Introduction

According to the 2022 Global Land Outlook report, humans have altered more than 70% of the Earth's land from its natural state, with agriculture having the greatest impact of all human activity and currently occupying 40% of all land area (UNCCD 2022). The global food system is a major source of greenhouse gas (GHG) emissions. Between 2007 and 2016, our food systems were responsible for between 10.8 to 19.1 Gt CO_2eq/year on average (IPCC 2019). Food systems are also the greatest cause of terrestrial biodiversity loss (UNCCD 2022). Despite these negative environmental outcomes, food systems can be reimagined and redesigned to better contribute to land restoration, biodiversity protection, and GHG mitigation. A suite of practices classified as 'regenerative agriculture' (RA) have been proposed to help achieve this, typically by sequestering carbon, increasing biodiversity, and improving soil health (Newton *et al* 2020). Despite the recent popularity of regenerative agriculture (as evident from the surge of articles and books that began to be published on the subject in 2015), there is no agreed consensus definition of what regenerative agriculture entails (Giller *et al* 2021, Newton *et al* 2020).

1.1. How is regenerative agriculture defined?

Reviews of literature on regenerative agriculture have concluded that it is frequently either defined by the practices it entails or the outcomes it seeks to achieve (Newton *et al* 2020, Schreefel *et al* 2020). A provisional definition of RA is '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 main practices included in regenerative agriculture definitions are minimal external inputs, mixed farming, minimal tillage, crop rotation, use of manure and compost, use of perennials, and other soil health improvement activities, while the overall objectives of regenerative agriculture center around improving soil, planet, human health, and/or profit (Schreefel *et al* 2020). A review of articles and practitioner websites found that the most commonly mentioned practices of regenerative agriculture included minimal external inputs, the use of on-farm inputs, integration of livestock, disuse of synthetic fertilizers or pesticides, no or reduced till, and use of cover crops (Newton *et al* 2020). Some of the most commonly mentioned objectives of regenerative agriculture from both practitioner websites and published articles were improving soil health, sequestering carbon, and increasing biodiversity (Newton *et al* 2020). In addition to these practices, other studies have focused more specifically on regenerative ranching and grazing practices, such as rotational grazing, adaptive multi-paddock grazing, or holistic planned grazing, which generally seek to increase stocking density, shorten rotation time, and extend post-grazing rest periods for paddocks (Rhodes 2017, Pecenka and Lundgren 2019, Gosnell *et al* 2020, Fenster LaCanne *et al* 2021). Indeed, the term 'conventional agriculture' also needs definition as it is frequently juxtaposed against 'other' agricultural practices, without any major consideration of its definition (Sumberg and Giller 2022). Some definitions of RA also vary in their descriptions to allow for regional specificity,that takes soil type, biophysical conditions, and human contexts into consideration to inform what practices and outcomes are best included (Lal 2020).

1.2. Regenerative agriculture and climate policy

Explicit consideration of RA is often lacking within policy structures (for example, as elements of the need for balancing food and fuel production, Schulte *et al* 2022), perhaps because of debates over its definition and its complex interaction with different agricultural paradigms, as argued by Page and Witt (2022). For RA to be promoted as a climate 'friendly' strategy will require careful consideration of its potential efficacy in different contexts. In particular, clarity is needed on what practices should be considered within the suite of RA. There is further a need to assess evidence of their impact on soil carbon sequestration. In this review, we compare and contrast the reported carbon storage potential of different RA practices from recent studies and identify routes to greater clarity on the impact of RA for sustainable agricultural policies.

2. Methods

2.1. Definition of regenerative agriculture practices relevant for carbon sequestration

For the purposes of this study, we followed the definitions of regenerative practices after Schreefel *et al* (2020): reduced or no-till, cover cropping, reduced use or disuse of agrichemicals such as mineral fertilizer and pesticides, the use of organic amendments such as compost and manure, crop rotation, increased perennialization and agroforestry, integration of crop and livestock systems, and improved grazing management, as illustrated in figure 1 and defined in table 1.

2.2. Identification of studies of RA farming practices which evaluate carbon storage

Studies on the seven individual practices were identified by using the titles of the seven defined practices (table 1) as search strings in Google Scholar. These were refined to only include those which were also identified by the search string 'soil carbon' (e.g. 'no-till soil carbon'). Initially, we only considered studies in which just one trait was changed from 'conventional' to 'regenerative' in isolation. This was expanded to include those in which several practices were changed from 'conventional' to 'regenerative' but the impacts of each could be disaggregated. Finally, we considered those studies that implemented a range of these practices as part of an overall shift to a regenerative system to evaluate the soil organic carbon dynamics when these practices were implemented simultaneously. This led to a total of 28 studies, published between 2002 and 2020 from which values for the reported rates of SOC were derived (table 2).

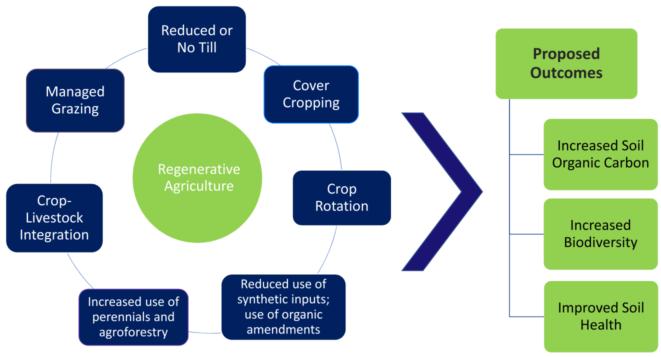

Figure 1. Common practices included in regenerative agriculture definitions/systems. Regenerative agriculture aims to increase soil organic carbon, increase biodiversity, and improve soil health through the implementation of these practices.

Table 1. Components of regenerative agriculture. Summary of definitions of practices typically considered as components of RA, adapted from Newton *et al* (2020), Schreefel *et al* (2020), Brewer and Gaudin (2020) and references therein.

Practice	Definition
Reduced or no till	Minimization of the tillage of soil during crop management, reducing soil compaction and plow-pans.
Cover cropping	Crops grown to replace bare fallow between growth cycles of the main crop (e.g. in winter), typically ploughed under as green manure.
Crop rotation	Cycling between different crops in different seasons.
Reduced/substituted input	Replacement or disuse of synthetic fertilizers, pesticides etc, and/or use of organic amendments as substitutes.
Perennials and agroforestry	Integration of cultivated perennials (multi-annual plants), including trees in the case of agroforestry.
Crop-livestock integration	Use of integrated crop-livestock (ICL) systems, with or without agroforestry (silvopasture).
Managed grazing	Use of regenerative ranching practices e.g. rotational grazing, adaptive multi-paddock grazing, or holistic planned grazing.

3. Results

3.1. What is the carbon sequestration potential of regenerative agriculture practices?

Soils represent a sizable carbon sink at the global level, where enhancing soil carbon sequestration is one mechanism by which emissions from agricultural activities could be mitigated. Estimates of historical SOC loss vary greatly, but commonly fall within the range of 55 to 78 Pg out of a total SOC pool of 1550 Pg (Lal 2004). Paustian *et al* (2016) estimate that the overall mitigation potential as a result of soil management practices is approximately 2.18 Pg C/year. Other studies estimate that under improved management practices, soil carbon sequestration rate estimates range from 0.4 to 1.2 Pg C/year (Lal 2004) or between 1 and 1.3 Pg C/year (Smith 2012). Many regenerative practices aim to increase soil carbon levels, but determining the exact levels of carbon increase depends on climatic conditions, soil type, duration since adopting the practice, and effective implementation.

The following sections investigate the range of possible carbon sequestration rates of each regenerative practice. The potential sequestration rates of each individual practice from studies reviewed are summarised in figure 2. Full details of the studies supporting these data are described in table 2.

3.1.1. Reduced- or no-till agriculture

No-till agriculture has frequently been recommended as a strategy to increase soil organic carbon levels. However, results from studies vary,and frequently only look at the carbon change in surface soils (Luo *et al* 2010). A meta-analysis found that, integrated across the top 30 cm of soils, converting from conventional till to no-till can increase SOC levels by 10% in temperate dry climates, 16% in temperate moist climates, 17% in tropical dry climates, and 23% in tropical moist climates - while converting to reduced till had a less pronounced effect compared to conversion to no-till (Ogle *et al* 2005). Another global meta-analysis indicated that no-till agriculture results in significant SOC increase compared to conventional till systems, finding that no-till agriculture could sequester 0.57 Mg C/ha/year (excluding wheat-fallow which showed no significant SOC change), reaching a new equilibrium in 15–20 years (West and Post 2002). Reduced till, however, was not shown to have resulted in significantly different SOC levels compared to conventional till (West and Post 2002). Reviews focusing on studies with deeper soil sampling found that no-till systems have a different vertical

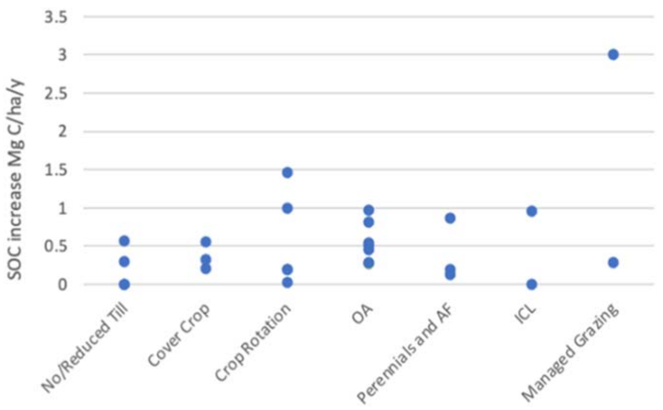

Figure 2. Studies and meta-analyses indicate that the SOC accumulation rates for individual farming practices that are often included within the definition of regenerative agriculture vary. OA rates here indicate both the SOC accumulation with a full/partial substitution of mineral fertilizer with organic amendments, or compared to control plots without amendments. Each point represents one study, points at 0 Mg C/ha/y indicate a nonsignificant increase in SOC.

Table 2. Summary of reported carbon storage data following application of the listed RA practice.

Practice	Reported rate of SOC accumulation
No or reduced till	*0%–23% across >20 years* (Ogle *et al* 2005) *No significant effect of reduced till, 0.57 Mg C/ha/year from no till over 5–15 years* (West and Post 2002) *No significant effect aggregating paired studies of 3- to 23- year duration* (Luo *et al* 2010) *0.3 Mg C/ha/year, all studies >5 years duration* (Angers and Eriksen-Hamel 2008, *Minasny et al 2017*)
Cover cropping	*0.32 Mg/ha/year for first 50 years* (Poeplau and Don 2015) *0.21 Mg C/ha/year, final-year values from studies of 1- to 30-year duration* (McClelland *et al* 2021) *0.56 Mg C/ha/year* (Jian *et al 2020*)
Crop rotation	*0.2 Mg C/ha/year, 5–15 years* (West and Post 2002) *0.2 Mg C/ha/year after 20 years (Minasny et al 2017)* *0.1 t CO_2eq/ha/year, diverse time durations (0.027 Mg C/ha/yr)* (Eagle *et al* 2011) *2.9 Mg C/ha (cover crops in rotation) 5.7 Mg C/ha (perennials in rotation) (from appendix: 1 Mg C/ha/yr with cover crops and 1.46 Mg C/ha/year with perennials)* (King and Blesh 2018)
Reduced use of agrichemicals and use of organic amendments	*9.4 Mg C/ha more than control, 5.6 Mg C/ha more than mineral fertilizer (0.45 Mg C/ha/yr compared to control and 0.27 Mg C/ha/yr compared to mineral fertilizer)* (Maillard and Angers 2014) *0.5 Mg C/ha/year (Minasny et al 2017)* *0.817 Mg C/ha/year (full substitution) 0.968 Mg C/ha/year (partial substitution), all >3 yr* (Wei *et al 2020*) *0.54 Mg C/ha/year to 0.82 Mg C/ha/yr inorganic and organic fertilizer meaning organic fertilizer sequesters 0.28 Mg C/ha/year more, 5–38 yrs* (Conant *et al* 2017)
Increased perennialization and agroforestry	*0.87 Mg C/ha/year (conversion to permanent vegetation/pasture), 5–38 yrs* (Conant *et al* 2017) *0.136 Mg C/ha/year (inclusion of perennials in rotation—0.5 t CO2/ha/y) 0.19 Mg C/ha/year (replacing annuals with perennials—0.7 t CO2/ha/y), typically >10 years* (Eagle *et al* 2011) *34% (SOC accumulation in 0–100 cm soil depth when converting from agriculture to agroforestry—from appendix calculated this to be 35.178 Mg/ha increase), durations not noted* (De Stefano and Jacobson 2018)
Integrated crop-livestock (ICL)	*No significant difference compared to continuous cropping with no till after 24 years* (Sato *et al* 2019) *0.96 Mg C/ha/year (with low/moderate grazing intensity) after 10 years* (Assmann *et al* 2014)
Managed grazing	*3 Mg C/ha/year over 10 years* (Teague *et al* 2016) *Effect size: .25 (calculated 28% higher SOC, absolute values not provided) for at least one season of measurement* (Byrnes *et al* 2018) *0.28 Mg C/ha/year, 5–38 yrs* (Conant *et al* 2017)

distribution of carbon throughout the soil horizon in comparison to conventional till systems. While carbon levels increased in the surface soils (0–10cm) under no-till, below this layer no-till systems had lower C contents - likely because conventional till causes an accumulation of SOC at a depth that corresponds to the plowing depth, and soils below 35–40 cm showed no significant change in SOC (Angers and Eriksen-Hamel 2008, Luo *et al* 2010). While Luo *et al* (2010) concluded that with the inclusion of deeper soils in the data, no-till resulted in an insignificant increase in soil C content, Angers and Eriksen-Hamel (2008) found that the surface level increase in soil C under no-till was enough to offset the loss in soil C in deeper soils, resulting in an average 4.9 Mg/ha more SOC under no-till. Given the average duration of studies of 16 years, this would suggest a SOC accumulation rate of approximately 0.3 Mg/ha/year - this is the same rate estimated by the review of studies by Minasny *et al* (2017).

3.1.2. Cover cropping

Cover crops can be included in regenerative systems to increase soil C, increase plant diversity on farms spatially or temporally, reduce bare fallow thereby reducing erosion, and provide additional nutrients to the soil (through the use of nitrogen-fixing leguminous cover crops and cover crop residues) (McClelland *et al* 2021). A meta-analysis of cover cropping treatments found that SOC increased by 0.32 ± 0.08 Mg/ha/year with the use of cover crops, and that the total mean SOC accumulation could reach 16.7 ± 1.5 Mg/ha by the time a new steady is achieved (Poeplau and Don 2015). A similar SOC accumulation rate was found by McClelland *et al* (2021) on temperate lands utilizing cover crops which accumulated SOC at a rate of 0.21 Mg C/ha/year. Others have predicted a higher rate of SOC accumulation. Jian *et al* (2020) found that in a meta-analysis of 131 global cover crop studies the inclusion of cover crops in rotations resulted in a carbon sequestration rate of 0.56 Mg C/ha/year. While cover cropping has been found to increase near surface SOC levels, different management factors could affect the rate of carbon accumulation in soils. For example, Jian *et al* (2020) found that multispecies cover crops and leguminous cover crops resulted in greater SOC increases compared with monoculture and grass species cover crops.

3.1.3. Crop rotation

Enhancing crop rotation can refer to transitioning from a monoculture system to continuous crop rotation, transitioning from a crop-fallow system to one that utilizes continuous cropping, or increasing the number of crops within a rotation system (West and Post 2002). Enhanced crop rotation often goes hand in hand with cover cropping practices,as cover crops can be utilized in rotation to reduce fallow or increase plant diversity within rotations. Enhancing crop rotation complexity has been found to increase SOC by a mean rate of 0.2 Mg C/ha/year (West and Post 2002) - the same rate estimated by Minasny *et al* (2017). A review of studies by the Nicholas Institute found that soil C response to diversifying crop rotations was highly variable, averaging near zero, with the exception of a rate of 0.027 Mg C/ha/year observed for systems transitioning from a monoculture to a more diversified rotation system, other than corn-soybean rotations (Eagle *et al* 2011). A larger impact was found from the decrease in N_2O emissions as a result of diversification, contributing to an average mitigation potential of 0.2 t CO_2eq/ha/year (Eagle *et al* 2011). However the majority of the studies included in this review considered only North American systems, and the effect of crop rotations could vary with climate conditions. Furthermore, the different types of plants (including species) included in rotations affects SOC accumulation rates: for example, the inclusion of cover crops and perennials in rotations was found to increase SOC levels by 2.9 Mg C/ha and 5.7 Mg C/ha respectively when compared to grain-only rotations (King and Blesh 2018).

3.1.4. Reduced use or disuse of synthetic agrichemicals and use of on farm organic amendments

Regenerative agriculture also requires minimizing the use of external inputs such as synthetic fertilizers or pesticides, and substituting these chemicals with farm-derived organic amendments such as compost, compost tea, and manure. Reducing the use of synthetic fertilizer can greatly mitigate GHG emissions associated with agricultural production given their extensive use and the greenhouse gas emissions associated with their production and application. FAO (2019b) have indicated that global demand for fertilizer nutrients ($N+P_2O_5+K_2O$) would reach 200.919 million tonnes by the end of 2022. Over half of this global demand is for nitrogen for fertilizer use - which results in approximately 2300 kilotonnes of N_2O emissions (FAO 2019a). A meta-analysis of 133 studies looking at the substitution of mineral fertilizer with organic fertilizer (manure, compost, or commercial organic fertilizer) found that full substitution with organic fertilizer could reduce GHG emissions by 0.203 Mg CO_2 eq/ha (0.055 Mg C/ha), while partial substitution could reduce emissions by 0.0672 Mg CO_2eq/ha (0.018 Mg C/ha) - however this does not consider the entire life cycle of both organic and mineral fertilizers (Wei *et al* 2020). While some studies suggest a significant mitigation potential by converting from mineral fertilizer to organic amendments the exact emissions reduction depends on the type of fertilizer being replaced, the rate of application, and maintaining yield so as not to offset GHG mitigation from decreased fertilizer use by increasing land-use conversion. GHG emissions associated with fertilizer production can vary greatly depending on the fertilizer product type and the raw materials used - emissions associated with different fertilizer product types of the same nutrient value can vary as much as 20% (Hasler *et al* 2015).

In addition to mitigating emissions associated with the production and application of mineral fertilizers, the use of on farm organic amendments can increase SOC levels by improving plant production and direct carbon input to the soil (Ogle *et al* 2005). Soils treated with manure are reported to have a SOC stock on average 9.4 Mg C/ha higher compared to control plots, and 5.6 Mg C/ha higher than those treated with mineral fertilizer (averaging about 0.45 Mg C/ha/yr and 0.27 Mg C/ha/yr respectively) (Maillard and Angers 2014). While both inorganic and organic fertilizers have been found to increase soil carbon levels, results from a meta-analysis reveal that soils treated with organic fertilizers sequester carbon at a faster rate (0.82 Mg C/ha/yr compared to 0.54 Mg C/ha/yr for inorganic fertilizers) (Conant *et al* 2017). Minasny *et al* (2017) estimate a SOC accumulation rate of 0.5 t C/ha/year with organic amendments. Wei *et al* (2020) found that when factoring in the rate of soil organic carbon sequestration (which increased by 0.968 Mg C/ha/year under partial substitution and increased by 0.817 Mg C/ha/year under full substitution) the net global warming potential of partial substitution with organic fertilizer was −3.6 Mg CO_2eq/ha and –3.2 Mg CO_2eq/ha with full substitution. While both these values indicate a considerable carbon sink as a result of substituting mineral fertilizers with organic fertilizers, it is important to note that the best results were derived from partial substitution rather than full substitution, partial substitution at a rate of 40%–60% increased yield by 11.5%, while full substitution decreased yield (Wei *et al* 2020). While some regenerative agriculture advocates may push for complete removal of mineral fertilizers or amendments, the evidence suggests that better results could result from reducing their use. A Life Cycle Analysis (LCA) of wheat production using mineral fertilizer, manure compost, and manure compost amended with biochar found that the majority of impact categories were mitigated under the different compost strategies and the overall environmental performance of the production systems improved (Jiang *et al* 2021). SOC was increased under all compost strategies. However the amount of SOC increase was much higher in the biochar amended strategies (Jiang *et al* 2021). Again, given that biochar would be considered an external input, there seems to be a need to further refine what exactly regenerative agriculture entails when it comes to reducing use or eliminating the use of external amendments (particularly in light of the need for greater circular economy closed-loop models in agrifood systems) - as this can be counter to the overall goals of maximizing carbon sequestration and reducing emissions while maintaining yield. However, it should be noted that some regenerative practitioners do make use of biochar amendments (Gosnell *et al* 2020).

Aside from fertilizer, regenerative agriculture also aims to reduce the use of other inputs such as pesticides. While the production of pesticides can also be energy intensive, their per hectare greenhouse gas emissions are much lower than those of nitrogen-based fertilizer (Eagle *et al* 2011). The extensive use of pesticides globally—over 4 million tonnes in 2019 (FAO 2019a)—is responsible for other negative environmental outcomes (the extent and nature of which differ according to different types of pesticides). Hence, there is a need within the regenerative agriculture discourse to consider and disaggregate considerations of pesticides according to their different classes and modes of action to avoid generalisations. While research on the harmful effects of pesticides often focuses on their toxicity to non-targeted plants and animals and the contamination that can spread off-farm, more recent research has observed the negative effect of some pesticides on soil microbial communities—including effects of some pesticides on the carbonic anhydrase enzyme which is involved in carbon sequestration (Nathan *et al* 2020). The reduction or disuse of pesticides can not only mitigate emissions from their production, but also have positive effects on soil microbial health and carbon sequestration (Jing *et al* 2022). However, the land-use implications of crop and yield losses from removal of pesticides from some cropping systems need to be considered to assess climate, biodiversity and other environmental impacts.

3.1.5. Increased perennialization and agroforestry

Regenerative systems that make use of increased perennialization and agroforestry can increase SOC by maintaining permanent soil cover, the addition of plant litter inputs, and increasing belowground inputs of C via their deeper rooting systems (Chenu *et al* 2019, De Stefano and Jacobson 2018, Schreefel *et al* 2020). Where land and labor systems allow, perennials and trees can be incorporated into farming systems, through a range of planting strategies including the use of perennial cover crops, diversified field margins, perennial forage, wind breaks, hedgerows, and alley cropping. Natural ecosystems such as grasslands and forests have strongly coupled nitrogen and carbon cycles due to permanent soil-vegetation interactions (Lemaire *et al* 2014)—a benefit which could in principle be replicated in agricultural settings through increased perennial production and agroforestry. Perennialization, and associated high belowground biomass C inputs, has been found to increase SOM in particulate organic matter and aggregate C compared to annual crop systems (Cates *et al* 2016). Conant *et al* (2017) estimate that conversion from annual crops to permanent vegetation can increase soil carbon at a rate of 0.87 Mg C/ha/year. Even the incorporation of perennials into annual crop rotations can increase soil carbon at an approximate rate of 0.136 Mg C/ha/year, while replacing annuals with perennials could sequester 0.19 Mg C/ha/year (Eagle *et al* 2011). Conversion from agriculture to agroforestry has been found to increase SOC stocks by 40% in the top 30 cm of soil, and by 34% overall in the top 100 cm (De Stefano and Jacobson 2018). In general, converting land-use from a less complex system to a more complex and diverse agroforestry system was found to increase SOC stocks. However, the high variability amongst agroforestry systems and inconsistencies in study design and sampling can make estimating the overall impact on soil carbon difficult to accurately assess (De Stefano and Jacobson 2018).

In addition to increasing SOC, perennialization and agroforestry can increase carbon storage through increased aboveground biomass as well. Remote sensing evidence indicates that in 2010 43% of all agricultural land had at least 10% tree cover. Total biomass carbon on agricultural land amounted to 47.37 Pg C, with trees making up a contribution 36.29 Pg C (Zomer *et al* 2016). Given that some regenerative systems include grassed waterways, buffer strips, hedgerows, silvopasture, and agroforestry (Lal 2020, Paustian *et al* 2020) there is the potential to increase carbon storage on regenerative farms via increased aboveground biomass compared to conventional systems. Giller *et al* (2021) highlight that of all the practices commonly included in regenerative agriculture, agroforestry has the greatest potential to carbon capture above and below ground.

3.1.6. Integratedcrop-livestock systems

Regenerative systems aim to integrate crop and livestock production, as opposed to more conventional continuous grazing and annual cropping systems where livestock and crop production are largely managed independently. Integrated crop-livestock (ICL) systems include a wide array of different management systems such as livestock integration into perennial systems (such as orchards or vineyards) with understory grazing, livestock integrated in rotation with a pasture or ley phase, or livestock grazing on cover crops or crop residues (Brewer and Gaudin 2020). Separate livestock and crop systems can result in poor nutrient cycling as a result of the decoupling of carbon and nitrogen cycles due to diminished soil-vegetation interactions. In contrast, integration through ley-based rotation systems temporarily capitalize on the benefits of leys to increase soil organic carbon levels and mitigate nitrogen loss (Lemaire *et al* 2014). The integration of crop and livestock systems also allows for the enrichment of soils from livestock manure, reducing the need for external fertilizers for crop production - contributing to a closed loop system that is less reliant on fossil fuel-based inputs. Additionally, annual cash crops in ICL systems have been shown to achieve similar yields to unintegrated systems which is beneficial in terms of land use efficiency and the potential for land-sparing, given the potential to generate more product per unit area (Peterson *et al* 2020). Despite these potential benefits, integrated crop-livestock systems remain understudied. While integration may help build SOC through enhanced biomass production, nutrient cycling, and improved biological and physical soil qualities,evidence on the overall impact is inconclusive and seems highly dependent on other management strategies being utilized, such as including tillage, forage species, stocking intensity and grazing management (Brewer and Gaudin 2020). A study of a 24-year crop-livestock integrated no-till system found that the total soil organic carbon content was similar to that of a continuous cropping no-till system, but higher than that of the continuous cropping system with conventional tillage (Sato *et al* 2019). de Sant-Anna *et al* (2017) similarly concluded that, compared to continuously cropped and plow-tilled systems, ICL systems had higher carbon stocks. However, they also found that carbon stocks in ICL systems varied with tillage and by phase (i.e. whether in the pasture phase or the cropping phase). Notably, both the ICL system with no-till sampled during the pasture phase, and the ICL system that was plow-tilled and sampled during the crop phase, had significantly higher carbon stocks. Grazing intensity has also been shown to affect carbon levels in ICL soils—a study in Brazil found that lower and moderate intensity grazing systems resulted in increasing total organic carbon levels at a rate similar to non-grazing treatment (about 0.96 Mg/ha/year), while the most intensive grazing resulted in much lower soil carbon stocks (Assmann *et al* 2014). Given the paucity of evidence, it is difficult to conclude how SOC levels respond to a transition to ICL systems, where the existing results seem to depend both on how the soils were previously managed and what other management practices are implemented alongside crop-livestock integration.

3.1.7. Managed grazing

Improved grazing management is an important aspect of regenerative ranching, whether this means rotational grazing, adaptive multi-paddock grazing, or holistic planned grazing (Colley *et al* 2020, Fenster, LaCanne *et al* 2021, Gosnell *et al* 2020, Paustian *et al* 2020, Pecenka and Lundgren 2019, Teague *et al* 2016, White 2020). Regeneratively managed grazing practices can be characterized by higher stocking density, short-duration grazing with frequent rotation, and long rest periods - differing from continuous grazing which has become increasingly common in developed countries (Colley *et al* 2020, Fenster, LaCanne *et al* 2021, Teague *et al* 2016). These methods are meant to maximize forage regrowth, prevent defoliation and bare ground, and increase above and belowground biomass which can be beneficial in building soil carbon (Gosnell *et al* 2020). A global meta-analysis found that rotational grazing significantly improved soil organic carbon (increasing SOC levels by approximately 28%) and bulk density soil conditions compared to continuous grazing. However more studies are needed to assess the impact of other variables such as climate on these results, and understand how differences within the classification of rotational grazing affect results (Byrnes *et al* 2018). Teague *et al* (2016) estimate that, with 100% implementation of grass-fed and finished beef production using adaptive multi-paddock grazing across North America, net livestock production emissions could fall from 0.056 Pg C/year to – 0.734 Pg C/year. This means that AMP grazing could sequester carbon at a total rate of 0.79 Pg/year, suggesting that the amount of carbon that can be sequestered in grazing soils is enough to offset overall livestock greenhouse gas emissions. This is based on a sequestration rate of 3 Mg C/ha/year, which was calculated based on a previous study on AMP grazing strategies by Teague *et al* (2011). A meta-analysis of grassland management studies found that improved grazing management resulted in a sequestration rate of 0.28 Mg C/ha/year (Conant *et al* 2017) - a rate that is much lower than that assumed by Teague *et al* (2016).

3.2. Implementation of a suite of regenerative practices

Many of these different practices that fall within the definition of regenerative agriculture have been demonstrated to increase SOC stocks and mitigate emissions to varying degrees. However, it is important to consider what the cumulative effect of the combined implementation of a number of these strategies could be. In particular, it is important to determine the extent to which there can be co-benefits or tradeoffs between different regenerative agriculture practices. Some studies of regenerative farming systems have found that the implementation of multiple practices has a beneficial cumulative effect. A study on regenerative almond farms in Spain found that farms that practiced no-till, used permanent natural covers, and organic amendments, and farms that used reduced tillage with green manure and organic amendments performed better in terms of soil quality improvements and SOC increase, compared to farms implementing fewer regenerative agriculture practices (e.g. reduced till and green manure, or reduced till and organic amendments) (Luján Soto, Martínez-Mena *et al* 2021). Perennial crop rotation systems had a higher SOC response compared to continuous annual and multi-crop annual systems, and no-till systems had a higher mean percentage change in SOC compared to conventional till system (McClelland *et al* 2021). This suggests that a combination of regenerative practices, cover cropping, crop rotation, no-till, and increased perennialization, can result in better outcomes for SOC than cover cropping alone. A study on the conversion of degraded cropland to multispecies pasture rotation which implemented a range of regenerative strategies (including no-till, no chemical fertilizers or biocides, holistic planned grazing, and introduction of other native plant species to move towards a silvopastoral system) found that over 20 years the SOC levels increased at a rate of 2.29 Mg C/ha/year - indicating a high carbon sequestration benefit from the conversion to regenerative agriculture methods (Rowntree *et al* 2020). Fenster, LaCanne *et al* (2021) analyzed results from multiple studies on regenerative systems to develop a regenerative scoring matrix, anddetermined that regenerative outcomes such as SOM, fine particulate organic matter, and total soil carbon increased with regenerative matrix scores. The furthermore indicated that no farm attribute reached an asymptote, indicating that implementing additional regenerative practices could continue to increase regenerative outcomes. However, other studies have observed evidence that when regenerative agriculture practices are combined, sequestration rates are impacted and do not exhibit a simple summative effect. West and Post (2002) found that enhancing rotation complexity while already using no-till did not result in a significant SOC increase - possibly because SOC was already closer to a maximum steady-state level compared to conventional till. Improved soil management may only increase carbon sequestration up to a certain limit, eventually reaching a saturation point, which imposes a ceiling on the sequestration potential of regenerative practices (Smith 2012, Stewart *et al* 2007). An additional limiting factor on the benefit of the adoption of a wide array of regenerative practices is the paucity of data on the impacts on yield. Some argue that regenerative agriculture could potentially result in declining yield, and thereby result in the need for the conversion of additional land for agricultural purposes (Giller *et al* 2021, Ranganathan *et al* 2020). While there is evidence that yield can be significantly lower on regenerative fields compared to 'conventional' (LaCanne and Lundgren 2018), others suggest that there is lack of data about lower yields from regenerative systems (Paustian *et al* 2020). While increasing yield may not be the most emphasised outcome of regenerative agriculture, there is some focus on yields that can be sustained long-term, particularly for lands that have seen productivity decline (Lal 2020, Rhodes 2017). A more balanced consideration of ecosystem health and restoration alongside consideration of yields, may prove beneficial towards sustaining yields in the long term.. Overall, more studies are needed to determine how different regenerative practices (alone or in combination) impact yield, as this will affect the overall environmental and agricultural outcome of their implementation. Regional and local soil characteristics should be taken into consideration when estimating the soil carbon sequestration potential of regenerative agriculture.Regenerative agroculture practices may increase SOC most in soils that are farthest from saturation levels due to degradation, but could have less of an impact on SOC levels in soils that are already near equilibrium.

3.3. Other environmental benefits of regenerative practices

Regenerative agriculture also aims to increase biodiversity (Newton *et al* 2020, Schreefel *et al* 2020), by reducing inputs that are harmful to biodiversity, increasing the diversity of on farm species (e.g. through use of perennials, agroforestry, cover crops, and crop rotations), and improving soil quality in a manner that can increase microbial biodiversity. A second-order meta-analysis review found that agricultural diversification contributes to enhanced biodiversity, pollination, pest control, and positive soil health outcomes, including improved fertility and water regulation, while having a net neutral effect on crop yield (although crop yield response was highly variable and context dependent) (Tamburini *et al* 2020). This suggests that as farms diversify (which aligns with regenerative agriculture in terms of non-crop and crop diversification and organic amendments) they better support biodiversity and may simultaneously benefit from enhanced ecosystem services. Studies of regenerative systems have found significant increases in biodiversity. A study on rangeland systems in the USA found that regenerative systems (which were characterized by higher stocking densities, shorter rotations, longer rest periods, no or low ivermectin use) had 19% more species in dung pat arthropod communities than conventionally managed rangelands (Pecenka and Lundgren 2019). Regenerative almond systems have also been shown to be beneficial for both soil microbial and invertebrate communities. Compared to conventional soils regenerative soils had significantly higher total microbial biomass, total bacterial biomass, gram-positive bacteria, and actinobacteria, as well as increased invertebrate richness and diversity (Fenster, Oikawa *et al* 2021). Visual soil assessments conducted by almond farmers in the Mediterranean drylands of Spain found almost all local indicators of soil quality were improved on regenerative fields in comparison to conventional fields, including the presence of ladybugs and Earthworms (Luján Soto, de Vente *et al* 2021)—suggesting that regenerative practices can improve habitats for diverse species. While regenerative practices can be supportive of different levels (e.g. intraspecies, species,community, ecosystem) and clades of biodiversity, more studies are needed to determine the effect that regenerative agriculture can have on biodiversity across trophic levels and across species. Given the acceleration of biodiversity loss and the expanse of land used for agriculture, emphasis must be not only on conserving biodiversity using farming practices, but also on land sparing for biodiversity conservation. While some studies suggest that regenerative agriculture practices can improve on-farm biodiversity in comparison with more conventional practices, there is a need for more systematic studies that compare specific regenerative practices against conventional practices, for their relative performance in reducing biodiversity losses of species that are threatened by agricultural practices and landscapes.

4. Discussion

Given the range of SOC values from these different regenerative agriculture practices, as illustrated in figure 2, the overall SOC rate with all practices ranges from 0.923–8.388 Mg C/ha/year, with crop rotation and managed grazing exhibiting the highest potential SOC accumulation rates. Agroforestry also has a large SOC potential; studies looking at the soil horizon from 0–100 cm compiled by De Stefano and Jacobson (2018) reported increased SOC by 35.178 Mg C/ha on average when converting to agroforestry, whereas crop rotations (including cover crops and perennials) raised SOC by between 2.9–5.7 Mg C/ha, and organic amendments increased SOC levels by 9.4 Mg C/ha compared to control (King and Blesh 2018, Maillard and Angers 2014). Aside from simply raising SOC, the reduction in use of synthetic fertilizers could contribute significantly to greenhouse gas emissions mitigation, while increased use of perennials and agroforestry could increase carbon storage via above and belowground biomass, deliveringfurther carbon savings from regenerative agriculture.r.

Aside from increasing SOC levels for GHG mitigation benefits, increasing SOC levels is also an important climate adaptation strategy. SOC is important in maintaining soil aggregate stability, lowering bulk density, improving water infiltration and water holding capacity, and reducing erosion and nutrient loss - these traits related to SOC content can make soils more resilient to extreme weather events which are becoming increasingly common and intense as a result of climate change (Al-Kaisi and Lal 2020). Given that regenerative agriculture practices have been shown to raise SOC levels over conventional practices, regenerative agriculture can also be considered as a climate adaptation strategy. During the 2012 drought, farmers in western Iowa who practiced no-till farming experienced higher corn yields than conventional tillagefarmers (6.2 Mg/ha in compared with 2.5 Mg/ha), suggesting that soil management practices can improve yield stability (Al-Kaisi *et al* 2013). However, in contrast, a meta-analysis on the yield stability of conventional, organic, and conservation agriculture revealed that the application of crop rotation, residue management, and no-tillage had no effect on yield stability (absolute or relative) compared to conventional till, and indicated that organically managed fields had a 15% lower relative yield stability (yield stability per unit yield produced) compared to conventional fields (Knapp and van der Heijden 2018). While it is important not to conflate conservation or organic agriculture with regenerative agriculture, this suggests the need for further analysis of which regenerative practices impact yield stability, whether negatively or positively, especially as unabated climate change will continue to impact on the agricultural landscape for the remainder of the 21st century and beyond. Despite these conflicting results from studies on yield stability, it is widely promoted that by increasing SOC levels, which regenerative agriculture practices tend to promote in contrast to conventional agriculture, it may be possible to increase the climate resilience of soils and farmers (Al-Kaisi and Lal 2020, Taylor *et al* 2021).

To maximise the carbon sequestration benefits of regenerative agriculture it is important to consider how these practices could be effectively scaled and implemented, either as individual practices or as RA packages. Scaling options could include incorporation into existing agri-environment schemes, or make use of accreditation to provide added value through consumer appeal. Schemes for providing legislative support have been developed through USDA and the EU Common Agricultural Policy (e.g. Al-Kaizi and Lal 2020, Gosnell *et al* 2020). Such schemes may also rely upon participatory approaches or be promoted through extension services (e.g. Luján Soto *et al* 2021). It is likely that all of these approaches will be needed in different combinations in different contexts. In the case of SOC, interactions with carbon credits may be critical where enhanced storage can be demonstrated: other practices may bring eligibility for local or regional schemes safeguarding biodiversity agricultural heritage or e.g. BurrenLife in Ireland (http://burrenprogramme.com/).

If the anticipated impacts are to be realised, it is important to consider the effectiveness of different regenerative agriculture practices, not only in terms of the amount of carbon sequestered, but also the permanence of soil carbon sequestration. A critical consideration is that soil carbon accumulation will slow over time as soils begin to reach a new equilibrium, meaning that carbon sequestration will not continue indefinitely. Indeed, the sequestered carbon could still be lost at any point and regenerative agriculture projections need to be clear that increasing soil carbon levels alone is not the key goal, but rather that increasing soil carbon levels to the point of equilibrium and then maintaining the levels is key to realising impacts. Furthermore, it must be acknowledged that the permanence of the carbon sequestered in soils is debated. Many regenerative agriculture practices interact solely with the labile carbon pool via additional of organic matter, meaning that carbon could easily be lost due to its short residence times and susceptibility to decomposition (Minasny *et al* 2017, Taylor *et al* 2021). Indeed, it could be more beneficial to convert soil organic matter into more passive or stable forms or carbon. Some research suggests that more stable forms of carbon may be made of microbial necromass or may be dependent on litter quality, aggregation, and bonding to the mineral soil matrix (Cotrufo *et al* 2013, Liang *et al* 2019). A study from India found that zero-till increased both labile soil carbon and recalcitrant soil carbon compared to conventional till (Sarkar *et al* 2021)—suggesting that regenerative agriculture practices may hold the potential to increase recalcitrant carbon pools as well as the total organic carbon level. More research effort could be directed at how to maximize accumulation of the recalcitrant fraction, and should continue to inform regenerative agriculture strategies.

Regenerative agriculture practices can have most potential for scaling in those farming systems and communities where they would be most effective. Scaling will further require supportive enabling environments, including policy and farmer uptake (Page and Witt 2022), which will need to be integrated with suites of the best practices over appropriate timescales. Such uptake will only scale if supported by relevant financial, institutional and policysupports. There has been significant research in the decision-making which underlies farmer adoption and future research will need to develop strategies which combine this with dissemination of accurate knowledge concerning probable impacts of different regenerative agriculture practices, whether deployed individually or as a suite of adaptations.

In general, soils that have been the most degraded from historical land use and management practices hold the most potential for increased adoption of regenerative agriculture practices, while other soils may be closer to equilibrium. In regions with inherently low SOC, it can be difficult to increase the C content, as high temperature enhances decomposition. In organic and peat soils, C content mostly will not increase—the aim canonly be to maintain the existing carbon levels (Minasny *et al* 2017). Soils with high clay content on the other hand may be associated with higher potential SOC levels (Minasny *et al* 2017, Smith 2012). Minasny *et al* (2017) found a tendency towards higher C sequestration potential (1–3%) on croplands with low initial SOC stock (topsoil less than or equal to 30 Mg C/ha). Zomer *et al* (2017) looked at the sequestration potential of global cropland soils and determined that North America had the highest potential for total carbon storage (0.17–0.35 Pg C/y), followed by South Asia and Europe (0.11–0.23 Pg C/y), demonstrating the important potential of these intensively cultivated regions. On a per hectare basis South Asia and North Africa have the highest potential for carbon storage, while on a national basis, countries with both high average increase and a large amount of cropland have the highest total annual potential for carbon storage - this includes the U.S., India, China, and Russia (Zomer *et al* 2017). Maximizing the anticipated benefits of regenerative agriculture will likely include consideration of these locations where there is a high potential for carbon storage, more specifically focusing on soils that are degraded from historical intensive agriculture. However, many of the soils which are most degraded can coexist with smallholders who are most marginalised, where the adoption of labour-intensive or land-extensive regenerative agriculture practices may be most challenging for a social and economic perspective.

5. Conclusion

Regenerative agriculture and its commonly included practices such as no or reduced till, cover cropping, crop rotation, reduced use or disuse of external amendments such as agrichemicals, the use of on farm organic amendments, increased use of perennials and agroforestry, integrated crop-livestock systems, and managed grazing are increasingly considered as strategies for reducing negative environmental impacts of 'conventional agriculture'. Individual regenerative agriculture practices can each help raise soil organic carbon levels which can both mitigate emissions and improve the overall soil quality,making it a strategy for climate adaptation as well. While some studies suggest that regenerative agriculture practices are even more effective when implemented in conjunction with each other, as would be more typical in a regenerative system, more research is needed into how these practices interact with each other and how soil carbon storage can be maximized and made more permanent by focusing on soils that are far from their potential storage capacity and the stability of the carbon within the soil matrix.

Data availability statement

No new data were created or analysed in this study.

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References

Al-Kaisi M M, Elmore R W, Guzman J G, Hanna H M, Hart C E, Helmers M J, Hodgson E W, Lenssen A W, Mallarino A P and Robertson A E 2013 Drought impact on crop production and the soil environment: 2012 experiences from Iowa *J. Soil Water Conserv.* **68** 19A–4A

Al-Kaisi M M and Lal R 2020 Aligning science and policy of regenerative agriculture *Soil Sci. Soc. Am. J.* **84** 1808–20

Angers D A and Eriksen-Hamel N S 2008 Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis *Soil Sci. Soc. Am. J.* **72** 1370–4

Assmann J M, Anghinoni I, Martins A P, Costa S E V G D A, Cecagno D, Carlos F S and Carvalho P C D F 2014 Soil carbon and nitrogen stocks and fractions in a long-term integrated crop–livestock system under no-tillage in southern Brazil *Agriculture, Ecosystems & Environment* **190** 52–9

Brewer K M and Gaudin A C M 2020 Potential of crop-livestock integration to enhance carbon sequestration and agroecosystem functioning in semi-arid croplands *Soil Biol. Biochem.* **149** 107936

Byrnes R C, Eastburn D J, Tate K W and Roche L M 2018 A global meta-analysis of grazing impacts on soil health indicators *J. Environ. Qual.* **47** 758–65

Cates A M, Ruark M D, Hedtcke J L and Posner J L 2016 Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter *Soil & Tillage Research* **155** 371–80

Chenu C, Angers D A, Barré P, Derrien D, Arrouays D and Balesdent J 2019 Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations *Soil Tillage Res.* **188** 41–52

Colley T A, Olsen S I, Birkved M and Hauschild M Z 2020 Delta life cycle assessment of regenerative agriculture in a sheep farming system *Integrated environmental assessment and management* **16** 282–90

Conant R T, Cerri C E P, Osborne B B and Paustian K 2017 Grassland management impacts on soil carbon stocks: a new synthesis *Ecological Applications* **27** 662–8

Cotrufo M F, Wallenstein M D, Boot C M, Denef K and Paul E 2013 The microbial efficiency-matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Glob Chang. Biol.* **19** 988–95

de Sant-Anna S A C, Jantalia C P, Sá J M, Vilela L, Marchão R L, Alves B J R, Urquiaga S and Boddey R M 2017 Changes in soil organic carbon during 22 years of pastures, cropping or integrated crop/livestock systems in the Brazilian Cerrado *Nutr. Cycling Agroecosyst.* **108** 101–20

De Stefano A and Jacobson M G 2018 Soil carbon sequestration in agroforestry systems: a meta-analysis *Agroforestry Systems* **92** 285–99

Eagle A, Henry L, Olander L, Haugen-Kozyra K, Millar N and Robertson G P 2011 Greenhouse gas mitigation potential of agricultural land management in the United States: a synthesis of the literature *Second Edition*

FAO 2019a *FAOSTAT* https://fao.org/faostat/en/#data

FAO 2019b Rome World Fertilizer Trends and Outlook to 2022

Fenster T L, LaCanne C E, Pecenka J R, Schmid R B, Bredeson M M, Busenitz K M, Michels A M, Welch K D and Lundgren J G 2021 Defining and validating regenerative farm systems using a composite of ranked agricultural practices *F1000Research* **10** 10115

Fenster T L, Oikawa P Y and Lundgren J G 2021 Regenerative almond production systems improve soil health, biodiversity, and profit *Frontiers in Sustainable Food Systems* **5** 256

Giller K E, Hijbeek R, Andersson J A and Sumberg J 2021 Regenerative agriculture: an agronomic perspective *Outlook on Agriculture* **50** 13–25

Gosnell H, Charnley S and Stanley P 2020 Climate change mitigation as a co-benefit of regenerative ranching: insights from Australia and the United States *Interface focus* **10** 20200027

Hasler K, Bröring S, Omta S W F and Olfs H W 2015 Life cycle assessment (LCA) of different fertilizer product types *Eur. J. Agron.* **69** 41–51

IPCC 2019 Summary for policymakers *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla *et al* (Geneva, Switzerland: IPCC)

Jian J, Du X, Reiter M S and Stewart R D 2020 A meta-analysis of global cropland soil carbon changes due to cover cropping *Soil Biol. Biochem.* **143** 107735

Jiang Z, Zheng H and Xing B 2021 Environmental life cycle assessment of wheat production using chemical fertilizer, manure compost, and biochar-amended manure compost strategies *Sci. Total Environ.* **760** 143342

Jing J, Cong W F and Bezemer T M 2022 Legacies at work: plant–soil–microbiome interactions underpinning agricultural sustainability *Trends in Plant Science* **27** 781–92

King A E and Blesh J 2018 Crop rotations for increased soil carbon: perenniality as a guiding principle *Ecological Applications* **28** 249–61

Knapp S and van der Heijden M G A 2018 A global meta-analysis of yield stability in organic and conservation agriculture *Nat. Commun.* **9** 3632

LaCanne C E and Lundgren J G 2018 Regenerative agriculture: merging farming and natural resource conservation profitably *PeerJ.* **6** e4428

Lal R 2004 Soil carbon sequestration impacts on global climate change and food security *Science* **304** 1623–7

Lal R 2020 Regenerative agriculture for food and climate *J. Soil Water Conserv.* **75** 123A–4A

Lemaire G, Franzluebbers A, Carvalho P C D F and Dedieu B 2014 Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality *Agriculture, Ecosystems & Environment* **190** 4–8

Liang C, Amelung W, Lehmann J and Kästner M 2019 Quantitative assessment of microbial necromass contribution to soil organic matter *Global Change Biol.* **25** 3578–90

Luján Soto R, de Vente J and Cuéllar Padilla M 2021 Learning from farmers' experiences with participatory monitoring and evaluation of regenerative agriculture based on visual soil assessment *Journal of Rural Studies* **88** 192–204

Luján Soto R, Martínez-Mena M, Cuéllar Padilla M and de Vente J 2021 Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture *Agriculture, Ecosystems & Environment* **306** 107191

Luo Z, Wang E and Sun O J 2010 Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments *Agriculture, Ecosystems & Environment* **139** 224–31

Maillard E and Angers D A 2014 Animal manure application and soil organic carbon stocks: a meta-analysis *Glob. Chang. Biol.* **20** 666–79

McClelland S C, Paustian K and Schipanski M E 2021 Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis *Ecological Applications* **31** e02278

Minasny B *et al* 2017 Soil carbon 4 per mille *Geoderma* **292** 59–86

Nathan V K, Jasna V and Parvathi A 2020 Pesticide application inhibit the microbial carbonic anhydrase–mediated carbon sequestration in a soil microcosm *Environmental Science and Pollution Research* **27** 4468–77

Newton P, Civita N, Frankel-Goldwater L, Bartel K and Johns C 2020 What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes *Frontiers in Sustainable Food Systems* **4**

Ogle S M, Breidt F J and Paustian K 2005 Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions *Biogeochemistry* **72** 87–121

Page C and Witt B 2022 A leap of faith: regenerative agriculture as a contested worldview rather than as a practice change issue *Sustainability* **14** 14803

Paustian K, Chenu C, Conant R, Cotrufo F, Lal R, Smith P and Soussana J-F 2020 Climate mitigation potential of regenerative agriculture is significant *Regenerative Agriculture Foundation June*

Paustian K, Lehmann J, Ogle S, Reay D, Robertson G P and Smith P 2016 Climate-smart soils *Nature* **532** 49–57

Pecenka J R and Lundgren J G 2019 Effects of herd management and the use of ivermectin on dung arthropod communities in grasslands *Basic Appl. Ecol.* **40** 19–29

Peterson C A, Deiss L and Gaudin A C M 2020 Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: a meta-analysis *PLoS One* **15** e0231840

Poeplau C and Don A 2015 Carbon sequestration in agricultural soils via cultivation of cover crops—a meta-analysis *Agriculture, Ecosystems & Environment* **200** 33–41

Ranganathan J, Waite R, Searchinger T and Zionts J 2020 *Regenerative agriculture: good for soil health, but limited potential to mitigate climate change* https://wri.org/insights/regenerative-agriculture-good-soil-health-limited-potential-mitigate-climate-change

Rhodes C J 2017 The imperative for regenerative agriculture *Sci. Prog.* **100** 80–129

Rowntree J E, Stanley P L, Maciel I C F, Thorbecke M, Rosenzweig S T, Hancock D W, Guzman A and Raven M R 2020 Ecosystem impacts and productive capacity of a multi-species pastured livestock system *Frontiers in Sustainable Food Systems* **4**

Sarkar D, Sinha A K, Danish S, Bhattacharya P M, Mukhopadhyay P, Salmen S H, Ansari M J and Datta R 2021 Soil organic carbon and labile and recalcitrant carbon fractions attributed by contrasting tillage and cropping systems in old and recent alluvial soils of subtropical eastern India *PLoS One* **16** e0259645

Sato J H, de Figueiredo C C, Marchão R L, de Oliveira A D, Vilela L, Delvico F M, Alves B J R and de Carvalho A M 2019 Understanding the relations between soil organic matter fractions and N_2O emissions in a long-term integrated crop–livestock system *Eur. J. Soil Sci.* **70** 1183–96

Schreefel L, Schulte R P O, de Boer I J M, Schrijver A P and van Zanten H H E 2020 Regenerative agriculture—the soil is the base *Global Food Security* **26** 100404

Schulte L *et al* 2022 Meeting global challenges with regenerative agriculture producing food and energy *Nat. Sustain.* **5** 384–8

Smith P 2012 Soils and climate change *Current Opinion in Environmental Sustainability* **4** 539–44

Stewart C E, Paustian K, Conant R T, Plante A F and Six J 2007 Soil carbon saturation: concept, evidence and evaluation *Biogeochemistry* **86** 19–31

Sumberg J and Giller K E 2022 What is 'conventional'agriculture? *Global Food Security* **32** 100617

Tamburini G, Bommarco R, Wanger T C, Kremen C, Heijden M G A V D, Liebman M and Hallin S 2020 Agricultural diversification promotes multiple ecosystem services without compromising yield *Sci. Adv.* **6** eaba1715

Taylor A *et al* 2021 Building climate change adaptation and resilience through soil organic carbon restoration in sub-saharan rural communities: challenges and opportunities *Sustainability* **13** 10966

Teague W R *et al* 2016 The role of ruminants in reducing agriculture's carbon footprint in North America *J. Soil Water Conserv.* **71** 156–64

Teague W R, Dowhower S L, Baker S A, Haile N, DeLaune P B and Conover D M 2011 Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie *Agriculture, Ecosystems & Environment* **141** 310–22

UNCCD 2022 *Summary for Decision Makers* (Global Land Outlook) 2nd edn

Wei Z, Ying H, Guo X, Zhuang M, Cui Z and Zhang F 2020 Substitution of mineral fertilizer with organic fertilizer in maize systems: a meta-analysis of reduced nitrogen and carbon emissions *Agronomy* **10** 1149

West T O and Post W M 2002 Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis *Soil Sci. Soc. Am. J.* **66** 1930–46

White C 2020 Why regenerative agriculture? *The American Journal of Economics and Sociology* **79** 799–812

Zomer R J, Bossio D A, Sommer R and Verchot L V 2017 Global sequestration potential of increased organic carbon in cropland soils *Sci. Rep.* **7** 15554

Zomer R J, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, Van Noordwijk M and Wang M 2016 Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets *Sci. Rep.* **6** 1–12