# REGENERATIVE AGRICULTURE AS A POTENTIAL ALTERNATIVE FOR FUTURE FARMING TO MITIGATE CLIMATE CHANGE

T.Geetha Jebarathnam
PROFESSOR, SCHOOL OF AGRICULTURE,
BHARATH UNIVERSITY, CHENNAI.
geetha.agri@bharathuniv.ac.in

## ABSTRACT

Regenerative agriculture is an all-encompassing farming approach that prioritizes improving biodiversity, strengthening soil health, and sequestering carbon to mitigate climate change. Through the resolution of numerous environmental and ecological concerns associated with modern agriculture, it offers a potential replacement for conventional farming methods. The main goals of organic farming are to restore ecosystems, soils, and biodiversity. Regenerative methods are endorsed by the organic movement since they are consistent with the organic principles of environment, health, justice, and compassion. Additionally, it makes an effort to cooperate positively with other participants and real regenerative farmers. Actually, the organic movement coined the term "regenerative agriculture" to describe the goals of organic farming. In reaction to the environmental difficulties and the state of the global climate, changes to more sustainable agri-food systems are needed. Recently, the EU recognized the potential of organic farming with the Farm to Fork aim of 25% organic agriculture in Europe by 2030. Global recognition of the contributions of organic farming and agro ecology towards addressing food security, climate change, and biodiversity loss has also been constant. At the same time, "regenerative agriculture" has grown in acceptance within agri-food firms, global governance, and international development circles in recent years. Traditional farming methods may result in soil degradation and decreased output.. The basic tenets of RA are to maintain soil cover, minimize soil disturbance, conserve living roots in the soil year-round, improve species variety, integrate livestock, and minimize or completely avoid the use of synthetic substances (such as fertilizers and pesticides). The main goals are to regenerate the soil and land and benefit the larger community in terms of the ecology, economy, and social conditions. Despite the alleged advantages of RA, the vast majority of farmers are hesitant to use these techniques since there isn't any concrete evidence of the benefits promised, and because there isn't any information on how effective these procedures are. Overuse of synthetic chemicals may result in ecological deterioration and a loss of biodiversity. Increased soil carbon content and a number of co-benefits can result from combining livestock with agriculture and agroforestry in the same region. But the advantages of RA techniques can differ between various agro ecosystems and might not necessarily be applicable across several agro ecological locations. In order to increase our understanding of the advantages and mechanisms connected to RA on regional scales, we advise the implementation of rigorous long-term agricultural system studies to compare conventional and RA techniques. In order to realize the social and economic benefits of RA practices and build resilience against climate change, this will give producers and policy-makers a solid evidence base from which to make decisions about implementing them.

[Keywords :Regenerative agriculture ,agroecosystems ,carbon sequestration food security, climate change, and biodiversity loss, biodiversity]

**INTRODUCTION:**

Regenerative agriculture (RA) is a farming technique that makes use of organic processes to boost biological activity, improve soil health, optimize nutrient cycling, restore the functionality of the landscape, and produce food and fiber while maintaining or boosting farm profitability. The approach is based on a set of guiding principles, and practitioners employ a range of strategies that combine biological and ecological processes with the aim of boosting production and regaining the functionality of the landscape.The goal of RA is to use natural ecological processes inside an agricultural system to increase the health of the farming system, not to restore the original pre-agriculture ecology and biological function. The term "regenerative agriculture" was first used by Gabel [1], and Rodale [2] expanded the idea of regenerative organic farming to include some options that encompass a holistic approach with a focus on environmental and social improvements without the use of chemical fertilisers and pesticides. Since then, several researchers have offered varied definitions of RA. Francis et al.'s [3] proposal for RA called for a focus on using farm-based resources while limiting the use of artificial inputs. The phrase is referred to as annual cropping by Project Drawdown [4]. Recently, producers, policymakers, scientists, and consumers have all given regenerative agriculture a lot of attention.The Intergovernmental Panel on Climate Change (IPCC) study on "Climate Change and Land" emphasized the significance of regenerative agriculture as well.

According to the paper, this technique of "sustainable land management" centered on ecological services "can be effective in building resilience of agroecosystems" Soil degradation and on going losses have been brought on by the existing intensive agriculture system. According to international scientists, there could not be enough soil available to feed the planet in the next 50 years. The world's biodiversity and soil fertility are both declining. To feed the world, keep global warming below 2 degrees Celsius, and stop biodiversity loss, it is necessary to regenerate soil on more than four billion acres of farmed agriculture. Regenerative agriculture is an all-encompassing farming method that emphasizes soil health, food quality, increased biodiversity, water quality, and air quality. Through techniques that raise soil organic matter, biota, and biodiversity, it enhances the health of the soil. Additionally, it attempts to increase carbon sequestration and water storage capacity.

Regenerative farming improves soil health, fosters biodiversity, and replenishes the soil with nutrients and carbon. The main factor in soil carbon sequestration and other ecological advantages is biodiversity. For plants to flourish, soil organic matter and carbon are essential.

Infiltration of water, retention of moisture, and nutrient cycling are all facilitated. Additionally, regenerative agriculture lessens erosion, offers food and habitat to a variety of species, and is more sustainable than conventional farming methods.Cover crops, livestock integration, and little to no tillage are all practices used in regenerative agriculture. Regenerative agriculture has numerous explanations and definitions. The lack of a singular definition may result in a number of issues that could affect the research agenda, funding, customer confidence, policies, and technological innovation.The defining characteristics of regenerative agriculture include minimizing the use of chemical fertilizers and pesticides, minimizing tillage, integrating animals, and utilizing cover crops.

Regenerative farming practices include the following:

•Minimize soil spread through conservation tillage

• Diversify crops to restore nutrients and break insect and disease lifecycles

• Keep soil covered with cover crops.

• Include livestock, which provides the soil with additional manure and acts as a source of carbon sinks.

Permanent pastures have a significant capacity to store water and carbon, which lowers runoff pollution and farm emissions. Crops grown on healthy soil have increased nutritional density and are more resistant to drought and floods. Regenerative agriculture employs a comprehensive systems approach that takes into account the wellbeing of farmers, animals, and the community as a whole to improve the ecosystem's health, starting with soil fertility. As a result, the effects of extreme weather brought on by a changing climate are lessened and resilience is increased. By using resources efficiently, sustainable agriculture guarantees that food is produced, increases the viability of farming, and enhances the quality of life for farmers. To maintain the status quo is implied by the term "sustainable," nevertheless. Utilizing only the resources at hand is the goal of sustainable farming methods.

Sustainable agriculture is similar to another strategy, referred to as agro ecology farming. Interactions between living things, including humans, animals, and the environment are made possible by this holistic viewpoint. Giving people a choice over both production and consumption improves the fairness of the food system. Sustainable land management, environmental protection, and the adaptation and mitigation of climate change are all supported by conservation agriculture. Through lower energy inputs and higher nutrient use efficiency, it is 20 to 50% less labor-intensive and helps lower greenhouse gas emissions. Additionally, it stabilizes and guards soil against disintegrating and releasing carbon into the atmosphere. Crop variety, rotation, and zero tillage are the three pillars of conservation agriculture. These maintain the soil's organic content and moisture, which aid in controlling weed growth, shield the soil from the effects of extreme weather patterns, and prevent compaction of the soil. In addition to improving plant nutrition and nutrient cycle, it also encourages pest and disease avoidance. It is also known as agro ecological farming, alternative agriculture, biodynamic agriculture, carbon farming, inclusive nature farming, conservation agriculture, green agriculture, organic regenerative agriculture, and sustainable agriculture. Regenerative agriculture is flexible, though, as there is no one method for regenerating soil that works for everyone. It is based on the idea that strong soils are the cornerstone of regenerative agriculture, enabling the symbiotic relationship between soil microbes and plants. Through photosynthesis, plants produce liquid carbon that the soil bacteria consume. Additionally, bacteria give plants essential nutrients like potassium, iron, calcium, and others that support their growth and well-being. As a result, plants produce nutrient-rich food for both animals and people. Therefore, it is essential to promote and advance regenerative agriculture.

**Potential advantages for soil health**:

The ability of soil to continue functioning as a vital living system within ecosystem and land-use boundaries, supporting biological production, maintaining air and water quality, and promoting plant, animal, and human health [14,15], has been referred to as soil health. Soil health was most recently described by the Intergovernmental Technical Panel on Soils (ITPS) as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems" [16]. The beneficial physical, chemical, biological, and biological (microbial diversity, N mineralization, and soil respiration) characteristics of soil that promote healthy, productive crops are attributed to the soil's health. These characteristics include soil texture, water holding capacity, pH, and soil organic matter (SOM). A large variety of both micro- and macrobiota that govern soil health are found there, making it a living, complex ecosystem. Soil is considered to be an active storage pool of C due to its capacity to store three times more carbon than the atmosphere [20]. One of the primary causes of soil degradation is the loss of soil organic carbon (SOC). SOC has been shown to improve soil structure, fertility, nutrient availability, aeration, water infiltration, and water-holding capacity [21]. Recently, it is also being considered as a solution for mitigating climate change [22]. According to the "4 per 1000" initiative launched by the French government at the 21st COP, an annual increment of 0.4% SOC in the first 30–40 cm of soil in all land uses could absorb a significant amount of $CO_2$ emitted due to human activities, with the co-benefits of improving soil health and food security. To meet this goal, stakeholders are encouraged to implement management practices that enhance SOC sequestration.

**Higher Soil Carbon**

Due to its ability to store three times as much carbon as the atmosphere, soil is thought of as an active storage pool of carbon (C) [20]. The loss of soil organic carbon (SOC), one of the main factors in soil deterioration, is a major problem. SOC has been demonstrated to enhance soil aeration, water infiltration, soil structure, fertility, and nutrient availability [21]. The idea of using it to mitigate climate change has recently gained some traction [22]. In accordance with the "4 per 1000" proposal unveiled by the French government at the 21st COP, an annual increase of 0.4% SOC in the first 30–40 cm of soil in all land uses might absorb a considerable quantity of CO2 produced as a result of human activity, with the added benefits of regenerative agriculture is a holistic farming system that focuses on soil health, food quality, biodiversity improvement, water quality and air quality There is broad agreement that even a little increase in SOC might have enormous benefits by restoring soil health [24,25,26], notwithstanding criticisms of the calculations and viability of the program in terms of combating climate change [23]. Additionally, there is anecdotal evidence that the "4 per 1000" target can be met in Mediterranean climate arable crops by utilizing mitigating techniques including no/minimal tillage, organic fertilizers, and stubble retention in coarse-textured soils [27]. Reduced agricultural yield is largely caused by decreased SOC stocks from terrestrial ecosystems. Optimizing agricultural yields calls for management strategies that raise SOC. A study found that increasing SOC by up to 2% increased wheat and maize yields and may lessen the need for N fertilizer [28,29]. in spite of soil carbon

**Minimum/No Tillage**

To minimize soil disturbance, RA farmers prioritize minimal or no tillage. The purpose of the approach, in addition to minimizing soil disturbance, is to promote the growth of fungal hyphae, which will improve nitrogen cycling in the soil. Carbon dioxide (CO2) fluxes to the atmosphere and water resources are brought on by soil disturbance brought on by intensive tillage [34]. In some nations, minimal or no tillage is commonly used not simply to reduce costs but also to benefit areas at risk of soil and water erosion. In addition to these advantages, some researchers think that using conservation tillage techniques can boost carbon sequestration, reducing the effects of global warming [35].Short-term soil carbon increases in Southeast Australia are improbable [41]; however, long-term soil organic matter (SOM) restoration may be possible [42] by introducing legume leys into grasses due to increased root biomass. Compared to short-term tillage methods, long-term tillage practices result in more perceptible variations in SOC [33,43]. Additionally, the amount of clay in the soil affects SOM accumulation. In clayey soils, tillage procedures decrease the stabilization of carbon (C) within micro aggregates, although they have little impact in sandy soils [44]. The principal source of SOC loss, according to research done in North America, was soil disturbance brought on by tillage, and significant SOC sequestration may be attained by moving from conventional to conservation tillage practices [45]. No-till (NT) farming has been promoted as a means of enhancing soil biological characteristics. When Martinez et al. (2013) [46] evaluated specific soil characteristics in irrigated Mediterranean no-till and conventional tillage (CT) systems, they found that soil chemical fertility increased under NT, with greater levels of N, P, and K. No-till produced higher carbon dioxide storage than traditional tillage. Under NT as opposed to CT, increased SOC led to higher biological activity. It has also been suggested that the chemical characteristics of the soil contribute to the greater productivity of NT soil. No-till farming, according to Powlson et al. [47], is helpful for soil quality but its ability to slow global warming is significantly overestimated.

**No tillage and increased yield**

No or minimal tillage has been shown in several studies to increase crop yields and profitability, depending on local agroclimatic conditions, crop, and soil characteristics. According to a meta-analysis of 740 paired measurements from 90 peer-reviewed articles, NT showed potential to reduce greenhouse gas emissions (GHG) in dry climates and reduced the global warming potential at acidic soil sites when compared to conventional tillage. It also increased barley yield by 49%. NT is suggested as a successful climate-smart agriculture (CSA) management method due to its potential to reduce climate change and increase agricultural yield. The overall impact of NT (in comparison to CT) is altered by a number of environmental and agronomic factors. Therefore, it is necessary to consider the agroecological setting.

**Cover crops ;**

Retaining stubble after harvest has numerous advantages, including reduced soil erosion and soil water run-off, returning nutrients to the soil, and increased carbon input and water infiltration [99]. Wind erosion is a serious problem in Western Australia, particularly in soils with fewer clay and silt particles, and can result in a 3% loss of carbon stocks up to a 1 m soil depth [100]. In general, stubble retention has a greater impact on C build-up when combined with other management practices [101]. Plant diversity influences the formation and accumulation of SOC through the decomposition and transformation of above- and below-ground plant litters [102]. Furthermore, the amount of carbon sequestered is affected by the quality of the residue C input (C:N ratio). Stubble with a higher C:N ratio decomposes slowly and thus adds more C to the soil, and vice versa. Horwath and Kuzyakov (2018) [103] proposed that N is required for SOC sequestration.

**Stubble retention:**

After harvest, leaving stubble in place has many benefits, including as decreasing soil erosion and runoff, replenishing the soil with nutrients, and improving water and carbon infiltration [99]. In Western Australia, wind erosion can lead to a 3% loss of carbon stocks up to a soil depth of one meter and is a significant issue, especially in soils with fewer clay and silt particles [100]. Generally speaking, when combined with other management techniques, stubble retention has a higher effect on C build-up [101]. Via the breakdown and transformation of above- and below-ground plant litters, plant variety affects the generation and accumulation of SOC [102]. Moreover, the quality of the residual C intake (C:N ratio) influences the quantity of carbon sequestered.

Using waste as a surface mulch is an additional strategy to increase soil biodiversity and SOC [113]. Depending on the kind of soil, adding stubble can have a significant [114,115] to insignificant [116] impact on carbon sequestration potential. More carbon is sequestered by stubble-incorporated clay soils than by sandy soils. A few studies have reported considerable increases in crop yield and SOC stocks when stubble retention is combined with no tillage [117, 118]. The effect of stubble retention on the productivity of succeeding crops is not well understood. Reducing cereal residue by 40–66% had a positive impact on wheat output in years with high levels of cereal residue, but a negative or no effect in years with low levels of cereal residue, according to Flower et al. (2017) [94]. Using waste as a surface mulch is an additional strategy to increase soil biodiversity and SOC [113]. Depending on the kind of soil, adding stubble can have a significant [114,115] to insignificant [116] impact on carbon sequestration potential. More carbon is sequestered by stubble-incorporated clay soils than by sandy soils. A few studies have reported considerable increases in crop yield and SOC stocks when stubble retention is combined with no tillage [117, 118]. The effect of stubble retention on the productivity of succeeding crops is not well understood. Reducing cereal residue by 40–66% had a positive impact on wheat output in years with high levels of cereal residue, but a negative or no effect in years with low levels of cereal residue, according to Flower et al. (2017) [94].

**Rotational Grazing:**

While farming is commonly cited for contributing to methane emissions, integrating livestock is another common RA technique to improve soil health and diversify the revenue stream [134]. Rotational grazing is preferable to continuous grazing for increasing SOC and enhancing soil health [135–138]. In certain grasslands, especially in drier and warmer areas, anecdotal data indicates that rotational grazing may boost SOC. Pasture management techniques have been shown to raise soil carbon reserves [139, 140]. Adaptive multi-paddock grazing works better than conventional grazing in terms of fixing N stocks and raising soil carbon [143]. Compared to heavy grazing, light to moderate grazing has been demonstrated to considerably increase SOC and soil structure [144,145]. Increased grazing efficiency combined with biodiversity management techniques may result in a significant build-up of SOC in the soil [147]. The complex relationship between grazing intensity and climate in drylands influences rates of carbon storage, organic matter deposition, and erosion, as was also shown by a recent large-scale assessment that was carried out across six continents [148].

**Enhanced Microbial Activity and Soil Biodiversity**

Because of their intricate relationships, soil biodiversity—which includes a broad variety of living things such as microorganisms and meso-, macro-, and megafauna—plays a significant role in the functioning of ecosystems [176,177]. In order to cultivate the healthiest, most nutritious food possible, counteract climate change, and restore 70% of the world's deteriorated soil fertility, RA methods place a strong emphasis on enhancing the functionality of soil microbes [178]. For the breakdown of organic matter, nitrogen cycling, and soil fertilization, the soil microbiota is crucial [19,179]. The development of a sound soil structure also depends on soil bacteria.

**Microorganisms' Function in a Stable Organic Carbon Fraction**

Most people assume that the majority of stable carbon components come from plant-derived C. Living microbial biomass contributes very little to sequestered carbon, making up only 5% of SOC [196,197]. However, it has been demonstrated that microbes play a crucial part in storing carbon in stable soil carbon pools [198,199]. There is growing evidence for the large contribution of microbial necromass to soil stable organic carbon. It has been demonstrated that microbial necromass contributes more than 50% of the total SOC in topsoil used in temperate agriculture. This suggests that microbial biomass is promoted by effective management techniques, which are essential for preserving healthy soils

[203]. The relative contributions of recalcitrant carbon fractions derived from plants and microbes are controversial, nevertheless, because of the shortcomings of the present SOM estimation techniques [204]. Necromass and microbial biomass seem to play a major role in controlling soil carbon storage, although the process by which necromass carbon stabilizes to stable soil carbon is not entirely understood [205].

**Cycle and Acquisition of Nutrients**

To cycle C, microbial CUE is crucial. Numerous critical roles in agricultural systems, such as plant productivity, control of the cycle of carbon and nitrogen, and favorable effects on animal output and production, have been related to the structure and biodiversity of the soil microbial community [18,206,207]. Microbial communities play a major role in the cycling of nutrients and C, and these processes are impacted by biotic and abiotic variables that can have either beneficial or negative effects [208,209]. When SOM decomposes, the majority of its nutrients are made available to plants because they have been mineralized [158]. One well-known function of mycorrhizal fungi is in the cycling of carbon, nitrogen, and phosphorus. It has been demonstrated that arbuscular mycorrhizal fungi (AMF) greatly increase zinc uptake in cereals. The plant species and zinc levels in the soil that are available to plants determine the mycorrhizal pathway for zinc uptake [211]. Weed suppression, pathogen control, and pest management

**Pest, Pathogen, and Weed Control/Suppression**

Worldwide, crop diseases, pests, and weeds cause large production losses and financial losses. Certain diseases and pests, especially those that are more prevalent in warmer climates, are expected to become more common and severe as a result of climate change. Plant immune responses are influenced by a number of factors, including elevated temperature, CO2, humidity, and nutritional status [256–259]. Pests and disease are encouraged by some agricultural practices, such as monocultures. Integrated disease and pest management is often advised to minimize subsequent losses. Although traditional fungicide/insecticide-based plant disease/pest control is one of the suggested approaches, it has a number of drawbacks. Numerous microorganisms found in soil, such as fungi and bacteria, have been shown to suppress disease and pests. Microbial biological control agents use a range of strategies, such as competition, hyperparasitism, and antibiosis, to shield crops against infections. Numerous microfauna, fungi, viruses, and beneficial soil bacteria have been identified as possible candidates for ecological balance restoration and biological control [260].Babikova et al. [261] found that mycorrhizal fungi can send defense signals from aphid-attacked plants to unaffected plants via their mycorrhizal network, giving intact plants an early warning.

Another strategy for cutting back on weedicide use is allelopathy. The number of weed seeds in the soil can be decreased by soil microorganisms like nematodes, bacteria, viruses, and fungi [267,268]. However, the majority of microbes are pathogens common to both crop plants and weeds, which is one of the main disadvantages of using microbes for weed control.

**Conclusion:**

In reaction to the difficulties presented by rising input costs and climate change, RA is becoming more popular. It is suggested that climate smart agriculture techniques, such as RA, be used to mitigate the effects of extreme weather events and lower greenhouse gas emissions.Restoring soil health is the main objective of RA, which is not a wholly new farming method but rather combines elements of well-established sustainable agricultural systems with the aim of revitalizing degraded land and benefiting a larger community on an environmental, economic, and social level. In addition, if the suggested management strategies are implemented, the system may aid in the sequestration of carbon. This review presents a complex picture to provide an evidence base that clearly outlines the advantages and disadvantages of implementing this technology because there is a dearth of empirical research comparing the benefits of a fully regenerated system against the traditional system. Researchers find it difficult to assess the alleged benefits of RA because there isn't a universally accepted definition of the condition. The various RA techniques covered in this review, however, have a good chance of producing results like improved soil health and, to a lesser degree, increased yields, according to solid scientific data Improved SOC is one of the most significant benefits of RA; it is essential for enabling nutrient cycling and supporting soil organisms as well as plants. Compared to the atmosphere, the carbon pool in the soil is more than three times larger. Changes in land use, particularly soil erosion and agricultural management practices, have led to a considerable reduction in soil carbon. Global carbon reserves will be impacted by climate change. For many years to come, agricultural soils will be the greatest carbon sink, according to strong scientific data; however, the amount of carbon sequestered depends primarily on the soil type and climate of the area. Combining regenerative farming techniques could improve the quality and capacity of the soil to sequester carbon. It appears that RA systems' viability and scalability will depend on site-specific studies proving their economic feasibility, given that growers are more inclined to move if there are no risks to their finances or the environment. Demand from customers for food that is unquestionably becoming safer and produced with environmentally friendly technologies. Scientists from all over the world are attempting to create these technologies, and there is growing evidence in science that different RA techniques may be able to stop soil deterioration, enhance soil health, and help dry land farmers produce food that is high in nutrients. However, it is extremely difficult for researchers to secure sufficient funding in order to comprehend, assess, and decipher the complexity of RA systems. . To create RA strategies that are specific to a given region, extensive research is needed. It is poorly known how diverse the soil is in various agro ecological zones, including Western Australia. To determine whether RA techniques enhance soil biological characteristics and fertilizer efficiency and thereby lessen dependency on synthetic inputs, long-term multidisciplinary research is required. Unlocking this potential and creating cutting-edge, economically viable regenerative farming technology suitable for the Mediterranean climate, along with extension initiatives that guarantee food and nutritional security and boost RA acceptance and implementation, depend heavily on government and industry support for research.

**References**

1. Gabel, M. Ho-Ping: A World Scenario for Food Production; World Game Institute: Philadelphia, PA, USA, 1979.

2. Rodale, R. Learning to Think Regeneratively. Bull. Sci. Technol. Soc. 1986, 6, 6–13. https://doi.org/10.1177/027046768600600104.

3. Francis, C.A.; Harwood, R.R.; Parr, J.F. The potential for regenerative agriculture in the developing world. Am. J. Altern. Agric. 1986, 1, 65–74. https://doi.org/10.1017/s0889189300000904.

4. Duchin, F. Drawdown the Most Comprehensive Plan Ever Proposed to Reverse Global Warming. Science 2017, 356, 811.

.14. Doran, J.; Sarrantonio, M.; Liebig, M. Soil Health and Sustainability. Adv. Agron. 1996, 56, 1–54. https://doi.org/10.1016/s0065- 2113(08)60178-9.

15. Doran, J.W. Soil health and global sustainability: Translating science into practice. Agric. Ecosyst. Environ. 2002, 88, 119–127. https://doi.org/10.1016/s0167-8809(01)00246-8.

16. ITPS 2020. Towards a Definition of Soil Health. Available online: https://www.fao.org/documents/card/fr/c/cb1110en/ (accessed on 13 March 2022).

18. Bender, S.F.; Wagg, C.; van der Heijden, M.G. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol. 2016, 31, 440–452.

19. Wagg, C.; Bender, S.F.; Widmer, F.; van der Heijden, M.G.A. Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc. Natl. Acad. Sci. USA 2014, 111, 5266–5270. https://doi.org/10.1073/pnas.1320054111.

20. Reeves, D. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 1997, 43, 131–167. https://doi.org/10.1016/s0167-1987(97)00038-x.

21. Robertson, F.; Armstrong, R.; Partington, D.; Perris, R.; Oliver, I.; Aumann, C.; Crawford, D.; Rees, D. Effect of cropping practices on soil organic carbon: Evidence from long-term field experiments in Victoria, Australia. Soil Res. 2015, 53, 636–646. https://doi.org/10.1071/sr14227.

22. Chabbi, A.; Lehmann, J.; Ciais, P.; Loescher, H.W.; Cotrufo, M.F.; Don, A.; SanClements, M.; Schipper, L.; Six, J.; Smith, P.; et al. Aligning agriculture and climate policy. Nat. Clim. Change 2017, 7, 307–309. https://doi.org/10.1038/nclimate3286.

23. Poulton, P.; Johnston, J.; acdonald, A.; White, R.; Powlson, . ajor limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob. Change Biol. 2018,

24, 2563–2584. 24. e Vries, W. Soil carbon 4 per mille: A good initiative but let′s manage not only the soil but also the expectations: omment on Minasny et al. Geoderma 292: 59–86. Geoderma 2018, 309, 111–112.

25. Lal, R. Promoting “4 Per Thousand” and “Adapting African Agriculture” by south-south cooperation: Conservation agri-culture and sustainable intensification. Soil Tillage Res. 2019, 188, 27–34.

26. Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; et al. The 4p1000 initiative: Opportunities, limitations and challenges

for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 2020, 49, 350–360.

27. Francaviglia, R.; Di Bene, C.; Farina, R.; Salvati, L.; Vicente-Vicente, J. . Assessing "4 per 1000" soil organic carbon storage rates under Mediterranean climate: A comprehensive data analysis. Mitig. Adapt. Strat. Glob. Change 2019, 24, 795–818. https://doi.org/10.1007/s11027-018-9832-x. Sustainability 2023, 15, 2338 28 of 43

28. Oldfield, E.E.; Bradford, M.A.; Wood, S.A. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 2019, 5, 15–32. https://doi.org/10.5194/soil-5-15-2019.

29. Kane, D.A.; Bradford, M.A.; Fuller, E.; Oldfield, E.E.; Wood, S.A. Soil organic matter protects US maize yields and lowers crop in-surance payouts under drought. Environ. Res. Lett. 2021, 16, 044018.

33. Nyiraneza, J.; Thompson, B.; Geng, X.; He, J.; Jiang, Y.; Fillmore, S.; Stiles, K. Changes in soil organic matter over 18 year in Prince Edward Island, Canada. Can. J. Soil Sci. 2017, 97, 745–756.

34. Sapkota, T.B.; Jat, M.L.; Aryal, J.P.; Jat, R.K.; Khatri-Chhetri, A. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. J. Integr. Agric. 2015, 14, 1524–1533. https://doi.org/10.1016/s2095-3119(15)61093-0.

35. Yang, X.; Drury, C.F.; Wander, M.M. A wide view of no-tillage practices and soil organic carbon sequestration. Acta Agric. Scand. Sect. B Soil Plant Sci. 2013, 63, 523–530. https://doi.org/10.1080/09064710.2013.816363.

36. Li, Y.; Li, Z.; Chang, S.X.; Cui, S.; Jagadamma, S.; Zhang, Q.; Cai, Y. Residue retention promotes soil carbon accumulation in minimum tillage systems: Implications for conservation agriculture. Sci. Total. Environ. 2020, 740, 140147. https://doi.org/10.1016/j.scitotenv.2020.140147.

37. Haddaway, N.R.; Hedlund, K.; Jackson, L.E.; Kätterer, T.; Lugato, E.; Thomsen, I.K.; Jørgensen, H.B.; Isberg, P.-E. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Évid. 2017, 6, 30. https://doi.org/10.1186/s13750-017- 0108-9.

41. Van Rees, H.; Jackman, A.; Baldock, J. Can Soil Organic Carbon Be Increased in a Continuous Cropping System in the Low to Medium Rainfall Zone? 2017. Available online: https://www.hartfieldsite.org.au/media/2017%20TRIAL%20RESULTS/Hart_Trial_Results_2017_Can_soil_carbon_be_increased_in_a_continuous_cropping_system_in_the_low_to_medium_rainfall_zone.pdf (accessed on 23 February 2022.

43. Cooper, H.V.; Sjögersten, S.; Lark, R.M.; Girkin, N.T.; Vane, C.H.; Calonego, J.C.; Rosolem, C.; Mooney, S.J. Long-term zerotillage en-hances the protection of soil carbon in tropical agriculture. Eur. J. Soil Sci. 2021, 72, 2477–2492.

44. Chivenge, P.; Murwira, H.; Giller, K.; Mapfumo, P.; Six, J. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Tillage Res. 2007, 94, 328–337. https://doi.org/10.1016/j.still.2006.08.006.

45. Baker, J.M.; Ochsner, T.E.; Venterea, R.T.; Griffis, T.J. Tillage and soil carbon sequestration—What do we really know? Agric. Ecosyst. Environ. 2007, 118, 1–5.

46. Martínez, E.; Fuentes, J.P.; Pino, V.; Silva, P.; Acevedo, E. Chemical and biological properties as affected by no-tillage and conventional tillage systems in an irrigated Haploxeroll of Central Chile. Soil Tillage Res. 2013, 126, 238–245.

47. Powlson, D.S.; Stirling, C.M.; Jat, M.L.; Gerard, B.G.; Palm, C.A.; Sanchez, P.A.; Cassman, K.G. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 2014, 4, 678–683. https://doi.org/10.1038/nclimate2292.

93. Nielsen, D.C.; Lyon, D.J.; Higgins, R.K.; Hergert, G.W.; Holman, J.D.; Vigil, M.F. Cover Crop Effect on Subsequent Wheat Yield in the Central Great Plains. Agron. J. 2016, 108, 243–256. https://doi.org/10.2134/agronj2015.0372.

94. Flower, K.; Ward, P.; Cordingley, N.; Micin, S.; Craig, N. Rainfall, rotations and residue level affect no-tillage wheat yield and gross margin in a Mediterranean-type environment. Field Crops Res. 2017, 208, 1–10. https://doi.org/10.1016/j.fcr.2017.03.012.

95. Myers, R.; Watts, C. Progress and perspectives with cover crops: Interpreting three years of farmer surveys on cover crops. J. Soil Water Conserv. 2015, 70, 125A–129A. https://doi.org/10.2489/jswc.70.6.125a.

96. Blanco-Canqui, H.; Claassen, M.M.; Presley, D.R. Summer cover crops fix nitrogen, increase crop yield, and improve soil–crop relationships. Agron. J. 2012, 104, 137–147.

97. Motisi, N.; Montfort, F.; Faloya, V.; Lucas, P.; Doré, T. Growing Brassica juncea as a cover crop, then incorporating its residues provide complementary control of Rhizoctonia root rot of sugar beet. Field Crops Res. 2009, 113, 238–245. https://doi.org/10.1016/j.fcr.2009.05.011.

98. Duff, J.; Firrell, M. Biofumigation: A Cover Crop Option 12 Months of the Year to Manage Three Soilborne Pathogens Ailing the Australian Vegetable Industry. Glob. J. Agric. Innov. Res. Dev. 2021, 8, 104–116. https://doi.org/10.15377/2409-9813.2021.08.8.

99. Packer, I.; Hamilton, G.; Koen, T. Runoff, soil loss and soil physical property changes of light textured surface soils from long term tillage treatments. Soil Res. 1992, 30, 789–806. https://doi.org/10.1071/sr9920789.

100. Harper, R.; Gilkes, R.; Hill, M.; Carter, D. Wind erosion and soil carbon dynamics in south-western Australia. Aeolian Res. 2010, 1, 129–141. https://doi.org/10.1016/j.aeolia.2009.10.003.

101. Saffigna, P.; Powlson, D.; Brookes, P.; Thomas, G. Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an australian vertisol. Soil Biol. Biochem. 1989, 21, 759–765. https://doi.org/10.1016/0038-0717(89)90167-3.

102. Cotrufo, M.F.; Soong, J.L.; Horton, A.J.; Campbell, E.E.; Haddix, M.L.; Wall, D.H.; Parton, W.J. Formation of soil organic matter via bio-chemical and physical pathways of litter mass loss. Nat. Geosci. 2015, 8, 776–779.

103. Horwath, W.R.; Kuzyakov, Y. The Potential for Soils to Mitigate Climate Change Through Carbon Sequestration. In Developments in Soil Science; Elsevier: Amsterdam, The Netherlands, 2018; Volume 35, pp. 61–92. https://doi.org/10.1016/b978-0-444- 63865-6.00003-x.

113. Tomar, V.P.S.; Narain, P.; Dadhwal, K.S. Effect of perennial mulches on moisture conservation and soil-building properties through agroforestry. Agrofor. Syst. 1992, 19, 241–252. https://doi.org/10.1007/bf00118782.

114. Freibauer, A.; Rounsevell, M.D.; Smith, P.; Verhagen, J. Carbon sequestration in the agricultural soils of Europe. Geoderma 2004 122, 1–23.

115. Liu, D.L.; Anwar, M.R.; O′ eary, G.; Conyers, M.K. Managing wheat stubble as an effective approach to se-quester soil carbon in a semi-arid environment: Spatial modelling. Geoderma 2014, 214, 50–61.

116. Campbell, C.A.; Gregorich, E.G.; Zentner, R.P.; Roloff, R.; Janzen, H.H.; Paustian, K.; Smith, W.; Liang, B.C.; McConkey, M.G. Carbon sequestration in the Canadian Prairies: Quantification of Short-Term Dynamics. SSSA Spec. Publ. 2001, 57, 93–114.

117. Xia, L.; Lam, S.K.; Wolf, B.; Kiese, R.; Chen, D.; Butterbach-Bahl, K. Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. Glob. Change Biol. 2018, 24, 5919–5932. https://doi.org/10.1111/gcb.14466.

118. Shi, J.; Wang, S.; Li, S.; Tian, X. ncreasing soil organic carbon sequestration and yield stability by no-tillage and straw-returning in wheat–maize rotation. Agron. J. 2022, 114, 1534–1545.

134. Seó, H.L.S.; Filho, L.C.P.M.; Brugnara, D. Rationally Managed Pastures Stock More Carbon than No-Tillage Fields. Front. Environ. Sci. 2017, 5, 87. https://doi.org/10.3389/fenvs.2017.00087. Sustainability 2023, 15, 2338 32 of 43

135. Díaz-Solís, H.; Grant, W.; Kothmann, M.; Teague, W.; Díaz-García, J. Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid rangelands. Agric. Syst. 2009, 100, 43–50. https://doi.org/10.1016/j.agsy.2008.12.007.

136. Teague, R.; Provenza, F.; Norton, B.; Steffens, T.; Barnes, M.; Kothmann, M.; Roath, R. Benefits of Multi-Paddock Grazing Management on Rangelands: Limitations of Experimental Grazing Research and Knowledge Gaps. Grasslands: Ecology, Management and Restoration; Nova Science Publishers: Hauppauge, NY, USA, 2008; pp. 41–80.

137. Teague, W.; Dowhower, S.; Baker, S.; Haile, N.; DeLaune, P.; Conover, D. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric. Ecosyst. Environ. 2011, 141, 310–322. https://doi.org/10.1016/j.agee.2011.03.009.

138. Byrnes, R.C.; Eastburn, D.J.; Tate, K.W.; Roche, L.M. A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators. J. Environ. Qual. 2018, 47, 758–765. https://doi.org/10.2134/jeq2017.08.0313.

140. Follett, R.; Stewart, C.; Bradford, J.; Pruessner, E.; Sims, P.L.; Vigil, M. Long-term pasture management impacts on eolian sand soils in the southern mixed-grass prairie. Quat. Int. 2020, 565, 84–93. https://doi.org/10.1016/j.quaint.2020.07.019

143. Mosier, S.; Apfelbaum, S.; Byck, P.; Calderon, F.; Teague, R.; Thompson, R.; Cotrufo, M.F. Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands. J. Environ. Manag. 2021, 288, 112409. https://doi.org/10.1016/j.jenvman.2021.112409.

144. Hiernaux, P.; Bielders, C.L.; Valentin, C.; Bationo, A.; Fernández-Rivera, S. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. J. Arid. Environ. 1999, 41, 231–245. https://doi.org/10.1006/jare.1998.0475.

145. Reeder, J.; Schuman, G. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environ. Pollut. 2001, 116, 457–463. https://doi.org/10.1016/s0269-7491(01)00223-8

147. Bai, Y.; Cotrufo, M.F. Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science 2022, 377, 603–608.

148. Maestre, F.T.; Le Bagousse-Pinguet, Y.; Delgado-Baquerizo, M.; Eldridge, D.J.; Saiz, H.; Berdugo, M.; Gozalo, B.; Ochoa, V.; Guirado, E.; García-Gómez, M.; et al. Grazing and ecosystem service delivery in global drylands. Science 2022, 378, 915–920. https://doi.org/10.1126/science.abq4062.

158. Wolf, B.; Snyder, G. Sustainable Soils: The Place of Organic Matter in Sustaining Soils and Their Productivity; CRC Press: Boca Raton, FL, USA, 2003.

176. Bardgett, R.D.; van der Putten, W.H. Belowground biodiversity and ecosystem functioning. Nature 2014, 515, 505–511. https://doi.org/10.1038/nature13855.

177. Wagg, C.; Schlaeppi, K.; Banerjee, S.; Kuramae, E.E.; Van Der Heijden, M.G.A. Fungal-bacterial diversity and microbiome complexity predict ecosystem functioning. Nat. Commun. 2019, 10, 4841. https://doi.org/10.1038/s41467-019-12798-y.

178. Brussaard, L.; de Ruiter, P.C.; Brown, G.G. Soil biodiversity for agricultural sustainability. Agric. Ecosyst. Environ. 2007, 121, 233–244. https://doi.org/10.1016/j.agee.2006.12.013.

179. Wagg, C.; van Erk, A.; Fava, E.; Comeau, L.-P.; Mitterboeck, T.F.; Goyer, C.; Li, S.; McKenzie-Gopsill, A.; Mills, A. Full-Season Cover Crops and Their Traits That Promote Agroecosystem Services. Agriculture 2021, 11, 830. https://doi.org/10.3390/agriculture11090830.

198. Miltner, A.; Bombach, P.; Schmidt-Brücken, B.; Kästner, M. SOM genesis: Microbial biomass as a significant source. Biodegradation 2012, 111, 41–55. https://doi.org/10.1007/s10533-011-9658-z.

199. Liang, C.; Schimel, J.P.; Jastrow, J.D. The importance of anabolism in microbial control over soil carbon storage. Nat. Microbiol. 2017, 2, 17105. https://doi.org/10.1038/nmicrobiol.2017.105.

205. Buckeridge, K.M.; Mason, K.E.; McNamara, N.P.; Ostle, N.; Puissant, J.; Goodall, T.; Griffiths, R.I.; Stott, A.W.; Whitaker, J. Environmental and microbial controls on microbial necromass recycling, an important precursor for soil carbon stabilization. Commun. Earth Environ. 2020, 1, 36. https://doi.org/10.1038/s43247-020-00031-4.

206. Delgado-Baquerizo, M.; Maestre, F.T.; Reich, P.B.; Jeffries, T.C.; Gaitan, J.J.; Encinar, D.; Berdugo, M.; Campbell, C.D.; Singh, B.K. Microbial diversity drives multifunctionality in terrestrial ecosystems. Nat. Commun. 2016, 7, 10541. https://doi.org/10.1038/ncomms10541.

207. Finn, D.; Kopittke, P.M.; Dennis, P.G.; Dalal, R.C. Microbial energy and matter transformation in agricultural soils. Soil Biol. Biochem. 2017, 111, 176–192. https://doi.org/10.1016/j.soilbio.2017.04.010.

208. Janus, L.R.; Angeloni, N.L.; McCormack, J.; Rier, S.T.; Tuchman, N.C.; Kelly, J.J. Elevated atmospheric CO2 alters soil microbial communities associated with trembling aspen (Populus tremuloides) roots. Microb. Ecol. 2005, 50, 102–109.

209. Sofi, J.A.; Bhat, A.G.; Kirmai, N.A.; Wani, J.A.; Lone, A.H.; Ganie, M.A.; Dar, G.I.H. Soil quality index as affected by different cropping systems in northwestern Himalayas. Environ. Monit. Assess. 2016, 188, 161. https://doi.org/10.1007/s10661-016-5154-1.

211. Coccina, A.; Cavagnaro, T.R.; Pellegrino, E.; Ercoli, L.; McLaughlin, M.J.; Watts-Williams, S.J. The mycorrhizal pathway of zinc uptake contributes to zinc accumulation in barley and wheat grain. BMC Plant Biol. 2019, 19, 133. https://doi.org/10.1186/s12870- 019-1741-y.

256. Panchal, S.; Chitrakar, R.; Thompson, B.K.; Obulareddy, N.; Roy, D.; Hambright, W.S.; Melotto, M. Regulation of Stomatal Defense by Air Relative Humidity. Plant Physiol. 2016, 172, 2021–2032. https://doi.org/10.1104/pp.16.00696.

257. Huot, B.; Castroverde, C.D.M.; Velásquez, A.C.; Hubbard, E.; Pulman, J.A.; Yao, J.; Childs, K.L.; Tsuda, K.; Montgomery, B.L.; He, S.Y. Dual impact of elevated temperature on plant defence and bacterial virulence in Arabidopsis. Nat. Commun. 2017, 8, 1808–1812. https://doi.org/10.1038/s41467-017-01674-2.

258. Williams, A.; Pétriacq, P.; Schwarzenbacher, R.E.; Beerling, D.J.; Ton, J. Mechanisms of glacial-to-future atmospheric CO 2 effects on plant immunity. N. Phytol. 2018, 218, 752–761.

259. Sun, Y.; Wang, M.; Mur, L.A.J.; Shen, Q.; Guo, S. Unravelling the Roles of Nitrogen Nutrition in Plant Disease Defences. Int. J. Mol. Sci. 2020, 21, 572. https://doi.org/10.3390/ijms21020572.

260. Ruiu, L. Microbial Biopesticides in Agroecosystems. Agronomy 2018, 8, 235. https://doi.org/10.3390/agronomy8110235.

261. Babikova, Z.; Gilbert, L.; Bruce, T.J.A.; Birkett, M.; Caulfield, J.C.; Woodcock, C.; Pickett, J.A.; Johnson, D. Underground signals carried through common mycelial networks warn neighbouring plants of aphid attack. Ecol. Lett. 2013, 16, 835–843. https://doi.org/10.1111/ele.12115.

267. Wagner, M.; Mitschunas, N. Fungal effects on seed bank persistence and potential applications in weed biocontrol: A review. Basic Appl. Ecol. 2008, 9, 191–203. https://doi.org/10.1016/j.baae.2007.02.003.

268. Harding, D.P.; Raizada, M.N. Controlling weeds with fungi, bacteria and viruses: A review. Front. Plant Sci. 2015, 6, 659. https://doi.org/10.3389/fpls.2015.00659.