

Review

Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health

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Abstract: Conventional farming practices can lead to soil degradation and a decline in productivity. Regenerative agriculture (RA) is purported by advocates as a solution to these issues that focuses on soil health and carbon sequestration. The fundamental principles of RA are to keep the soil covered, minimise soil disturbance, preserve living roots in the soil year round, increase species diversity, integrate livestock, and limit or eliminate the use of synthetic compounds (such as herbicides and fertilisers). The overall objectives are to rejuvenate the soil and land and provide environmental, economic, and social benefits to the wider community. Despite the purported benefits of RA, a vast majority of growers are reluctant to adopt these practices due to a lack of empirical evidence on the claimed benefits and profitability. We examined the reported benefits and mechanisms associated with RA against available scientific data. The literature suggests that agricultural practices such as minimum tillage, residue retention, and cover cropping can improve soil carbon, crop yield, and soil health in certain climatic zones and soil types. Excessive use of synthetic chemicals can lead to biodiversity loss and ecosystem degradation. Combining livestock with cropping and agroforestry in the same landscape can increase soil carbon and provide several co-benefits. However, the benefits of RA practices can vary among different agroecosystems and may not necessarily be applicable across multiple agroecological regions. Our recommendation is to implement rigorous long-term farming system trials to compare conventional and RA practices in order to build knowledge on the benefits and mechanisms associated with RA on regional scales. This will provide growers and policy-makers with an evidence base from which to make informed decisions about adopting RA practices to realise their social and economic benefits and achieve resilience against climate change.

Keywords: soil health; regenerative agriculture; soil carbon; microbial function



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1. Introduction

Regenerative agriculture (RA) is a farming strategy that uses natural processes to increase biological activity, enhance soil health, improve nutrient cycling, restore landscape function, and produce food and fibre, while preserving or increasing farm profitability. The strategy is based on a set of guiding principles, and practitioners use a variety of tactics that integrate biological and ecological processes with the objective of increasing production and restoring landscape functionality.

The objective of RA is not to restore the native pre-agriculture ecology and biological function, but rather to leverage ecological processes in nature within an agricultural system to improve farming system health. The term “regenerative agriculture” was first coined by Gabel [1], then Rodale [2] further developed the concept 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 definitions of RA have been put forward by various researchers. Francis et al. [3] proposed that RA emphasises the use of resources found on the farm while restricting the use of synthetic inputs. Project Drawdown [4] uses the term to refer to annual cropping systems that include at least four of six sustainable practices without the system being organic. Sherwood and Uphoff [5] and Rhodes [6] proposed that RA is a system built on biological principles that seeks to enhance both productivity and environmental management. Conversely, systems that reduce soil fertility, carbon storage, and biodiversity are considered as degenerative agriculture.

In order to address these concerns, the Food and Agricultural Organisation (FAO) proposed that the aim of RA is to go beyond the “do no harm” principles of sustainable agriculture [7]. According to a SYSTEMIQ report, RA is one of the 10 transitions needed to transform food and land use. In general, it includes approaches that regenerate soil, reduce the use of synthetic pesticides and fertilisers, and have a positive impact on the environment [8]. RA is considered to achieve the target specified by United Nations Sustainable Development Goal 2: “By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality”.

Despite there being various descriptions of RA, there is no agreed definition, which poses considerable challenges for researchers, farmers, agriculture advisors, policy-makers, and consumers in understanding and applying RA concepts. Recently, researchers and policy-makers have attempted to define regenerative agriculture to guide future research and policy development. Based upon a qualitative analysis of 28 studies, Schreefel et al. [9] proposed a provisional definition of RA as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production”. By contrast, Newton et al. [10] using a meta-analysis approach found that many RA definitions were either process- or outcome-based or, in a few instances, a combination of both. Hence, they proposed that “individual users of the term ‘regenerative agriculture’ to define broadly for their own purposes and contexts”.

Five principles that guide the approach are as follows: (1) minimise soil disturbance, (2) keep the soil covered year-round, (3) keep live plants and roots in the soil for as long as possible, (4) incorporate biodiversity, and (5) integrate animals. Advocates and practitioners of RA argue that these methods will prevent soil erosion and depletion, actively build soil, provide appropriate crop nutrients with minimum external inputs, produce healthy, high-yielding crops with few weeds and pests, limit greenhouse gas emissions, increase farmers’ financial returns, and improve human health (Figure 1). However, such claims have been widely criticised, and the general consensus is that they are not supported by rigorous empirical science [11].

RA practitioners use a number of methodologies that combine biological and ecological systems to increase productivity and restore landscape function. The overarching goal is to capitalise on natural processes, including by doing the following:

1. Capturing soil carbon through the photosynthesis of high-biomass-producing plants.
2. Improving symbiotic soil microbiota–plant interactions.
3. Using biological systems to enhance soil structure and water retention.
4. Including livestock, with an anticipated positive impact on ecosystem services.

There is no universal approach; instead, these practices must be tailored to the specific farming and climatic environment in which they are used. Factors such as precipitation, temperature, soil type, farm enterprise mix, markets, and individual preferences must be addressed before implementing an RA system. Furthermore, RA is not organic farming

and is not a prescriptive agricultural method. Rather, it is based on core concepts that assist individuals in implementing a variety of techniques on their properties in order to achieve the desired outcomes. Many of the practices used by RA farmers are well-established “good farming” practices that conventional farmers also use. Some RA practices overlap with other forms of sustainable agriculture practices, such as conservation agriculture, organic farming, low-input farming, climate smart agriculture, and carbon farming.

RA Principles	RA Practices	RA Benefits	Microbial Mechanisms
<ul style="list-style-type: none"> • Minimise soil disturbance • Keep soils covered • Keep living roots in soil year round • Encourage diversity • Integrate livestock 	<ul style="list-style-type: none"> • No/minimum tillage • Stubble retention • Diverse crop rotations • Multispecies cover crops • Intercropping • Composting and use biostimulants • Rotational grazing • Reduce synthetic inputs 	<ul style="list-style-type: none"> • Improved soil health through <ul style="list-style-type: none"> • Increased soil carbon • Improved microbial functions and associated nutrient cycling • Improved soil moisture • Improved resilience to pests and diseases • Nutrient rich food • Reduced greenhouse gas emissions 	<ul style="list-style-type: none"> • Liquid carbon pathway • Improved uptake of water and minerals • Enhanced soil aggregation, plant growth and photosynthesis

Figure 1. RA (Regenerative Agriculture) principles, practices, and purported benefits and mechanisms to improve soil health.

Significance of Regenerative Agriculture to Western Australian Farming Systems

Australian drylands comprise approximately 372 million ha of agricultural land, encompassing grazing and cropping, and most of the cropping zones have a semi-arid climate. Soils are predominantly coarse textured with inherently low soil carbon. Land degradation is a major issue facing Australian agriculture; two-thirds of agricultural land is already degraded due to erosion, declining soil fertility, salinity, acidification, and declining rainfall [12]. Australia is the world’s driest inhabited continent, thus it is important to quickly develop and implement strategies to prevent further land degradation and restore soil health. Otherwise, these issues could lead to an increased propensity for desertification.

Among grains, wheat is the dominant commodity in Australia, with an annual production of 25 million tons, followed by barley and canola (<https://www.aegic.org.au/australian-grain-production-a-snapshot/> Australian Export Grains Innovation Centre, accessed on 20 September 2022). Western Australian grain production today is predominantly a system of continuous high-input, high-output cropping. There are many emerging issues associated with this approach; in particular, farm profitability is declining due to reduced seasonal rainfall in the major grain-growing regions, posing financial risks if crop failure occurs. Declining soil fertility, herbicide/pesticide resistance, consumer concerns about the use of glyphosate and other environmental issues, plateauing grain production, and increasing competition from other international export markets, particularly in the Black Sea region, are some of the other challenges for the grain industry [13]. In the face of these challenges, Australian growers will need to embrace new opportunities to sustain the profitability of grain production. Farmers are responding to these challenges in different ways. For instance, some farmers are shifting their focus from maximising yield to maximising

profit, and some are moving towards lower-risk systems or diversification of cash crops. The farmer-led effort for the adoption of RA principles and practices is another example of a shift in focus towards reduced cashflow risk and increased returns. Several cost-effective farming practices are already in use that would be consistent with RA principles. Three main anticipated outcomes of RA are assumed: the agricultural ecosystem will regenerate, landscape functions will improve, and farming will remain profitable.

Despite the perceived benefits of RA, wide-scale adoption has not been achieved on a global scale. Barriers to adoption include biophysical, cultural, social, institutional, and economical concerns, and the major barrier is the lack of regionally specific knowledge, science-based evidence, and bio-economic models for transitioning from conventional systems to RA. The aims of the current review were (1) to examine the purported outcomes of RA against the current scientific evidence, and (2) to identify knowledge gaps for future research. Two broadly reported benefits are that RA helps to sequester and/or retain carbon in the soil and improves soil biology. Based on literature searches for peer-reviewed scientific evidence on the benefits of RA, almost no scientific studies have been conducted directly in the context of RA. However, there are numerous peer-reviewed scientific publications on individual RA practices reporting their influence on soil carbon and soil biology. Therefore, the focus of the review shifted to looking at the scientific evidence (local and overseas studies) on RA practices that affect soil carbon build-up and improve soil health.

2. Potential Benefits of RA for Soil Health

Soil health has been defined as the ability of soil to continue to function as a vital living system within ecosystem and land-use boundaries, thereby sustaining biological productivity, maintaining air and water quality, and promoting plant, animal, and human health [14,15]. More recently, the Intergovernmental Technical Panel on Soils (ITPS) defined soil health as “the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems” [16]. The health of soil is attributed to its desirable physical (texture, water holding capacity), chemical (pH, soil organic matter (SOM), and biological (microbial diversity, N mineralisation, and soil respiration) properties that support healthy productive crops. Soil is considered a living and complex ecosystem harbouring a wide array of both micro- and macrobiota that regulate its properties. The intensification of agriculture with modern technology has deteriorated the capacity of soil to maintain its functions, affecting long-term productivity and causing a loss of ecosystem services [17–19]. Improving soil health by increasing organic matter and boosting its fertility and productivity is the primary focus of RA.

2.1. Increased Soil Carbon

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 CO₂ 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.

Despite criticisms of the calculations and achievability of the initiative in terms of mitigating climate change [23], there is broad consensus that even a small increase in SOC could provide tremendous benefits by restoring soil health [24–26]. Moreover, there is anecdotal evidence that the “4 per 1000” target could be achieved in arable crops in the Mediterranean climate by using mitigation strategies including no/minimum tillage, organic fertilisers, and stubble retention in coarse-textured soils [27]. Diminishing SOC

stocks from terrestrial ecosystems are a major concern for declining agricultural production. Management practices that increase SOC are recommended to optimise agricultural yields. Increasing SOC up to 2% has been shown to increase yield in maize and wheat, and may reduce reliance on N fertiliser [28,29]. Although soil carbon build-up is influenced by regional climate and management practices [30], phenomena such as deforestation, fire, land use conversion, and erosion are attributed to a loss of SOC. In particular, land cultivation removes topsoil, destroys soil aggregate structure, and exposes SOC to oxidation, affecting nutrient availability and soil physical properties [23,31–33]. Several cropping practices implemented to maintain or increase SOC are discussed below.

2.1.1. Minimum/No Tillage

A key practice used by RA farmers is minimum or no tillage to minimise soil disturbance. Among the other benefits of minimising disturbance to the soil, the practice is aimed at allowing fungal hyphae to proliferate, thus enhancing nutrient cycling in the soil. Soil disturbance due to extensive tillage causes carbon dioxide (CO₂) fluxes to the atmosphere and water resources [34]. Minimum or no tillage is widely adopted in some countries not only as a cost-saving means, but also to provide benefits in areas prone to soil and water erosion risk. Aside from these benefits, some experts believe that conservation tillage methods can increase carbon sequestration, thereby mitigating the consequences of global warming [35].

Minimum tillage combined with residue retention in a double-cropping system is the most promising management strategy for increasing SOC stocks in croplands [36]. Increased SOC stock or concentration in the topsoil not only supports more productive soil with increased biological activity, but also promotes resilience to harsh weather conditions. Haddaway et al. (2017) [37] based upon a global metanalysis suggested that the increased C stock under no tillage versus high tillage in the upper soil (0–30 cm) was around 4.6 Mg/ha (0.78–8.43 Mg/ha, 95% CI) over ≥ 10 years, while no effect was detected in the full soil profile [38]. In contrast, SOC accumulation was found to be insignificant with continuous cropping under zero tillage in a warm semi-arid temperate or sub-tropical climate; however, slow accumulation of SOC was possible with the inclusion of perennial pastures in rotation [39,40]. Increasing SOC with conservation tillage depends upon several factors, including precipitation, soil depth, crop yield, stubble retention, and decomposition rate [40].

Soil carbon is unlikely to increase with current farming practices in Southeast Australia in the short-term [41]; however, incorporating legume leys into grasses could restore soil organic matter (SOM) in the long-term due to increased root biomass [42]. Long-term tillage practices produce more noticeable changes in SOC than short-term tillage practices [33,43]. Furthermore, SOM storage is modulated by the clay content of soil. Tillage practices reduce carbon (C) stabilisation within microaggregates in clayey soils but have little effect in sandy soils [44]. According to studies conducted in North America, soil disturbance caused by tillage was the primary cause of SOC loss, and substantial SOC sequestration could be achieved by switching from conventional to conservation tillage practices [45].

To improve soil biological properties, no-till (NT) farming has been proposed. Martinez et al. (2013) [46] discovered that soil chemical fertility increased under NT, with higher levels of N, P, and K, when they compared selected soil properties in irrigated Mediterranean no-till and conventional tillage (CT) systems. Compared to conventional tillage, no-till sequestered more C. Increased SOC resulted in higher biological activity under NT than CT. The increased productive capacity of NT soil has also been proposed in terms of soil chemical properties. Powlson et al. [47], however, asserted that while no-till is beneficial for soil quality, its role in mitigating climate change is greatly exaggerated.

Differences in SOC increase with tillage practices in different soil profiles have been reported, which may be due to discrepancies in the methodologies used to determine SOC. Soils were only sampled to a depth of 30 cm or less in almost all cases where conservation tillage was found to sequester C, even though crop roots often extended much

deeper. Conservation tillage showed no consistent accrual of SOC in a few studies where sampling extended deeper than 30 cm, with higher concentrations either near the surface in conservation tillage or in deeper layers in conventional tillage. These disparities may be due to differences in thermal and physical conditions caused by tillage, which affect root growth and distribution. Another study that used gas exchange measurements on a maize/soybean rotation for 2 years discovered no C sequestration in either conservation or conventional tillage, suggesting that long-term studies and deeper soil sampling are needed in order to improve the predictability of C sequestration potential with changes in tillage practices [48].

No Tillage and Yield Improvement

Several studies have indicated a positive impact of no or minimum tillage on crop yields and profitability, subject to regional agroclimatic conditions and crop and soil factors. When compared to conventional tillage, NT reduced the global warming potential at acidic soil sites, increased barley yield by 49%, and showed potential to reduce greenhouse gas emissions (GHG) in dry climates, according to a meta-analysis of 740 paired measurements from 90 peer-reviewed articles [49]. As a result of its potential to mitigate climate change and improve crop yield, NT is recommended as an effective climate-smart agriculture (CSA) management practice. However, various environmental and agronomic variables alter the net effect of NT (compared to CT). Therefore, the agroecological context must be taken into account when comparing different tillage techniques. In contrast, from a study of historical wheat yield patterns under NT and CT, [50] concluded that the tillage system had no effect on wheat yield and that Australian wheat varieties were not adapted to the NT system.

On its own, no tillage is not considered beneficial in certain circumstances, especially where stubble decomposes very quickly. Nouri et al. (2019) [51] demonstrated that long-term incorporation of cover crops, particularly vetch, in conjunction with NT improved the physical properties of soil, such as soil aggregation and moisture retention during dry spells. A study conducted on deep sands in the central wheatbelt of Western Australia over a 7-year period revealed that different tillage treatments had no effect on crop yields; however, soil carbon and microbial function increased under CT and NT treatments in the top 0.10 and 0.05 m of soil, respectively [52]. Using data from 678 peer-reviewed publications, a global meta-analysis assessed the impact of various crop and environmental variables on NT relative to CT yields. The study found that the impact of NT on yield varied depending on the region, with yield declining in tropical regions with maize-based systems and increasing in moisture-limited arid regions [53]. A long-term tillage experiment demonstrated that, in a semi-arid subtropical environment, it would take at least 20 years to achieve the full soil benefits (physical, chemical, and biological) of an NT system [54]. When NT was used instead of traditional tillage, yield increased by 47 and 28%, respectively, with and without the use of N and Zn fertilisers.

The prevailing environmental conditions of a region have the greatest influence on carbon sequestration and, as a result, crop yields. A recent global analysis of NT-induced changes in soil C and crop yield based on 260 and 1970 paired studies, respectively, revealed that compared to CT, conservation agriculture benefits arid regions the most by achieving a win–win outcome of increased C sequestration and crop yield. In more humid areas, only SOC gains are likely to occur, with no effect on crop yield, whereas in some colder areas there will be a negative impact on both SOC and yield [55]. According to these studies, adopting conservation management practices in Western Australia would result in a win–win situation. Sun et al. [55], however, emphasised the need for more rigorous and long-term studies evaluating the regional climate-related benefits of such practices.

Despite the variability in responses to the NT effect on increasing SOC, a substantial amount of literature has demonstrated that SOC can potentially be increased using NT in conjunction with crop residue retention and mixed rotation, with a plausible positive impact on crop yield [56–58]. According to the literature, the addition of organic residues such as

compost, biochar, and manure can result in significant SOC gains [59]. However, critics of RA deny the validity of such claims and state that most of these studies lack the proper methodology for measuring and verifying SOC changes [23]. With modern techniques such as hyperspectral remote sensing, it may be possible to provide SOC predictions in the future.

Scientific evidence from overseas and limited studies in Western Australia indicate that C sequestration is possible in moderately degraded soils in warm arid zones by using improved farming practices. Any system in which the input of biomass-C exceeds the loss (due to decomposition, erosion, etc.) will result in soil organic carbon sequestration (Dr Rattan Lal, The Ohio State University, Columbus, USA, personal communication, July 2020). There is also inorganic carbon in arid and semi-arid regions. According to the published literature, a significant increase in SOC is expected 6–10 years after a change in management practices (NT and rotational complexity), with an equilibrium reached after 15–20 years under constant weather conditions. Increased SOC can lead to a higher crop yield, which can be attributed to increased plant available water holding capacity and N availability, particularly in N-deficient soils. While a critical SOC threshold of 2% is established for sustainable crop production in temperate regions and about 1% in tropical regions [60], it would be worthwhile to investigate the minimum critical SOC threshold for cereals and other rotational crops in Western Australia's Mediterranean climate. Importantly, management practices that boost SOC are site-specific. Furthermore, SOC loss from wind erosion in dryland agriculture in the region necessitates research into farming practices that can prevent such SOC loss. Identifying the best socioeconomically feasible practices for increasing SOC storage in Western Australian soils will not only improve soil quality and long-term productivity, but also aid in implementing the key principles of RA.

No-Tillage and Nitrous Oxide (N₂O) Emissions

Despite the advantages of NT management practices for increasing SOC, there are concerns that they result in higher N₂O emissions. This is concerning, as even a small concentration of this gas has a large effect on warming, which could offset the benefits of an NT system [61,62]. Increased N₂O with NT is attributed to a higher use of N fertilisers causing denitrification, possibly due to low organic matter in combination with low oxygen conditions and low soil pH and texture [63–65]. Changing from diverse perennial systems with high SOM to an annual cropping system causes high N₂O flux due to greater mineralisation and denitrification [66]. Conversely, some studies have predicted low emissions of N₂O from NT compared with CT systems in the longer term [67]. Management strategies are required to mitigate the impact of N₂O emissions from reduced- or no-till agriculture. It is suggested that enhanced-efficiency nitrogen fertilisers be used to reduce N₂O emissions [68]. Plant diversity can also reduce N₂O emissions in restored agricultural soils [69]. The type of cover crop used may also influence N₂O emission rates. Leguminous crops, for example, can increase crop productivity while having no effect on N₂O emissions due to their ability to fix atmospheric N [70]. Organic and inorganic fertilisers have been shown to reduce nitrogen loss while increasing N accumulation in soils when used together [71]. Furthermore, matching N supply to crop demand, in conjunction with animal waste and residue management, can reduce N₂O emissions by 0.38 Tg N₂O-N [72].

Another major issue with NT is the overuse of herbicides for weed control, which causes environmental pollution and resistant weeds, and threatens human health. It may be possible to reduce herbicide use under no-till crop production by using an integrated approach such as crop competitive enhancement, seed bank reduction technologies, crop rotation and biological control [73–75].

2.1.2. Cover Crops

The second and third RA principles involve keeping soil covered and living roots in the soil all year. One method is to incorporate cover crops into the farming system. Cover crops are typically grown between main crops to cover and keep living plants on

the soil during non-cash-cropping periods. This is accomplished by either planting cover crops after harvest or under-seeding cash crops, typically grains, with perennial crops that will then develop to maintain soil cover post-harvest into the following season. Cover crops can be single species or multi-species blends. Despite the ease with which single cover crop species can be managed, a mixture of species may provide all the benefits of each species in the mix [76]. Multi-species cover crops, including legumes, are thought to improve ecosystem functions such as biological nitrogen fixation, microbial diversity, compaction reduction, attraction of beneficial insects, suppression of weeds, regulation of soil temperature, and increased water infiltration. Cover crops, in addition to improving soil fertility, aid in carbon sequestration, and their widespread adoption could reduce agricultural GHG emissions by 10%, which is comparable to using no-till or other cropping practices [77]. One of the key benefits of cover crops is enhanced microbial biomass through the addition of extra SOM in soil [78]. However, it can take several years for soil carbon to increase significantly [79,80]. A variety of cover crop responses to SOC accumulation have been reported on a global scale in various agroclimatic regions. Cover cropping was shown to increase surface storage of SOC in a temperate humid region of North America by the use of cover crops six times in eight years, improving soil functionality, but profitability was dependent on the type of production system used [81]. The mechanism of SOC storage with cover crops remains unknown; it could be due to either below- or above-ground biomass input or rhizodeposition.

Soil carbon accumulation with cover crops has been linked to soil texture, with an increase in soil carbon more likely to occur in clay soils with cover crops. In Argentina, studies have shown that cover crops grown on fine- and coarse-textured soils accumulate more soil carbon [82]. While cover crops can help eroded soils with low C content accumulate more carbon [83,84], the benefits are more visible with no tillage due to a slower rate of residue decomposition than with conventional tillage [85]. A recent meta-analysis of 131 global studies found that incorporating cover crops into the rotation significantly improved SOC, with fine-textured soils showing the greatest increase; the increase was greater in shallow soil (30 cm) than in subsurface soil (>30 cm). This increase in SOC was associated with improvements in soil quality and mineralizable N and C, and was influenced by the annual temperature, number of years after cover cropping began, initial SOC concentration, and latitude [86].

Plant diversity is important in both natural and managed systems and is thought to be essential for maintaining soil productivity. Crop diversification provides a multitude of benefits, including increased crop productivity and biodiversity, suppression of pests and pathogens, and improved water and soil quality [87]. Without the use of nitrogen fertilisers, legume cover crops have a positive impact on the yield of the subsequent main crop [88]. A meta-analysis of 1001 paired observations from 121 papers found that species mixes increased SOC content and stock by 6–8% more than monocultures [89]. The researchers concluded that the functional groups within the mixtures had little effect on increasing SOC but did have an effect on increasing microbial biomass carbon when compared to monocultures. Crop rotation and mixed species cover crops combined with no tillage restored degraded cropland and increased C stocks in tropical sandy soils in just five years [90]. In contrast, recent modelling indicates that increasing the cover crop area by 30% could increase annual C stocks by 35 Tg within 50 years [91].

Furthermore, the mechanisms by which cover crops influence the yield of subsequent crops can vary among cropping systems and environments and are thus poorly understood [92,93]. Cover crops have been shown to have a negative effect on gross margins in Western Australia's low-rainfall environments [94]. Another concern is that cover crops planted in the summer will consume all available moisture, which will be detrimental to subsequent crops, especially if dry conditions prevail at the start of the season. However, yield improvement in corn and soybean has been reported after cover crops in a dry year [95]. Similarly, increased yields of main crops after summer cover crops were attributed to reduced compaction and soil temperature, and increased soil aggregate sta-

bility, carbon, and nitrogen concentration and soil water content [96]. Conversely, a 10% reduction in wheat yield has been reported following cover cropping [93]. Furthermore, cover crops may harbour pests and diseases that infect subsequent crops, although there is evidence that mustard cover crops have a biofumigation effect and can lessen the impact of soil-borne pathogens [97,98]. In order to garner the benefits of this technology in dryland agriculture, careful management and selection of cover crop species are required.

Due to high temperatures and a lack of summer rain, cover cropping is infeasible in Western Australia's north-central and north-eastern low-rainfall zones, whereas in the south, where summers are relatively cooler, sowing cover crops may be opportunistic, depending on the frequency and intensity of summer rain events. Growers must balance profitability and long-term soil health benefits when incorporating cover crops into their cropping programmes.

2.1.3. Stubble Retention

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. A 50-year study on vertisol at the Hermitage in Queensland, Australia, found that stubble retention and N fertilisation improved soil health and kept soil carbon levels stable [104]. The addition of N fertiliser to a system combining stubble retention and no tillage improved soil aggregate formation, which influenced C sequestration [105,106] and microbial community structure [107], whereas other studies found insignificant effects on SOC [108,109]. Burning stubble harms physical, chemical, and biological properties, decreases SOM, and contributes to GHG emissions [110]. Fifty percent of WA growers burn narrow windrows to control weeds, and this practice has been shown to deplete C stocks [111]. Over a 19-year period, no tillage combined with stubble retention yielded 2–5% SOC compared to 1.5% with tillage and stubble burning [112].

Another way to improve soil biodiversity and SOC is to use residue as a surface mulch [113]. The effect of incorporating stubble on carbon sequestration potential ranges from large [114,115] to negligible [116] and is dependent on soil type. Clay soils with incorporated stubble sequester more C than sandy soils. A few studies have found that when no tillage was combined with stubble retention, crop yield and SOC stocks increased significantly [117,118]. There is little information available on the impact of stubble retention on the yield of subsequent crops. Flower et al. (2017) [94] found that reducing cereal residue by 40–66% had a beneficial effect on wheat yield in years with high levels of cereal residue but a negative or no effect in years with low residue levels.

While stubble retention has been advocated to promote soil health, it can be detrimental in terms of spreading stubble-borne diseases that impact crop production. However, the negative consequences can be mitigated by implementing integrated disease management approaches.

2.1.4. Crop Rotation and Diversity

Crop rotation, also known as diversification, is a centuries-old practice that improves yield and profit by providing nutritional benefits and breaking the pest–disease–weed cycle. However, crop rotation as a practice reverted to monocultures in the middle of the last century due to a heavy reliance on inorganic fertilisers and pesticides, improved crop vari-

eties, and, in some cases, economic considerations. All of these eventually resulted in land degradation and the loss of SOM [119]. Crop rotation is becoming increasingly recognised for its potential to improve soil quality [120], crop yield, and water use efficiency [121].

Recent research has found that crop rotation improves soil functionality and SOC [122]. Blair and Crocker (2000) [123], in a long-term experiment in New South Wales Australia, discovered that including some legume-based rotational crops increased the concentration of labile carbon and potentially improved the soil structure. Another recent Australian study in NSW revealed that SOC was generally higher in native or grazing fields compared to cultivated fields, while precipitation and land management on specific farms may have a role in SOC distribution [124]. The Mediterranean climate of Western Australia is characterised by high summer temperatures, irregular rainfall, and low cloud cover. Such circumstances will limit the soil's ability to sequester carbon. Lopez-Bellido et al. [125], in a 29-year long-term experiment in a rainfed Mediterranean climate, demonstrated that no tillage combined with legume crop rotation was critical to improving soil fertility and increasing both C levels and its rate of accumulation by soil. A global meta-analysis of 69 field experiments consisting of 276 paired experiments compared C sequestration rates in response to reduced tillage intensity or increased rotation complexity. A shift from CT to NT significantly increased C sequestration, with crop rotation adding even more C [126]. The SOC increase may be minimal or non-existent in the first 2–5 years following a change in management practice, but that may be followed by a significant increase in the next 5–10 years [127,128].

Deep-rooted perennials may benefit from sequestering SOC at greater depths, especially in marginally productive soils. Over a 22-year period, a comparison of SOC sequestration potential and stocks in tagasaste (a woody N-fixing perennial) and annual crops in high rainfall zones of WA revealed that tagasaste had a higher C sequestration rate and stock to a depth of 0.9 m [129]. In a study conducted in the Albany sand plain of Western Australia, Hoyle et al. [130] reported that the actual SOC was consistently highest in perennial pastures across all soil types. The main factors influencing SOC, which was higher in annual pastures than in mixed or continuous cropping, were soil depth and rainfall. They also noted that the topsoil surface under perennial pastures is already saturated with SOC, and that even with a 30% decrease in rainfall in the future, any additional increase in SOC storage capacity under mixed or continuous cropping would be in less than 0.1 m of the soil surface. Cropping practices that include rotating with high-residue-producing crops, as well as maintaining surface residue cover and reducing tillage, can significantly increase SOC and N [131]. However, crop rotation had little effect on SOC in fertile soil of WA [111]. Pulse crops contribute significantly to biological nitrogen fixation, and as a result improve SOC. However, the yield benefit of wheat and pulse crop rotation is more dependent on the type of pulse crop in rotation than SOC, because some pulse crops produce comparatively lower biomass and residue inputs [132].

Sanderman [133] examined the C sequestration potential of Australian soils and concluded that while management practices such as enhanced rotation, no till, and stubble retention clearly increased SOC compared to conventional practices, SOC stocks decreased over time, implying that the practices likely mitigated C losses rather than sequestered additional SOC.

2.1.5. Rotational Grazing

Another popular RA practice is to integrate livestock to improve soil health and diversify the income stream, despite the fact that livestock farming is widely blamed for contributing to methane emissions [134]. To increase SOC and improve soil health, rotational grazing is preferred over continuous grazing [135–138]. Anecdotal evidence suggests that rotational grazing may increase SOC in some grasslands, particularly in drier and warmer climates. According to reports, pasture management practices can increase soil carbon stocks [139,140]. However, in south-eastern Australia, a survey using paired-site sampling found no difference in SOC stocks in different pasture and management practices,

with the exception of higher SOC in improved pastures, which the authors attributed to methodological issues [141]. Sanderman et al. [142] discovered that rotational grazing had little effect on SOC in a subsequent study in Southern Australia. Rotational grazing of pastures, however, increased SOC in the 0–40 cm layer by about 25% more than no-till fields [134].

In terms of increasing soil carbon and retaining N stocks, adaptive multi-paddock grazing outperforms conventional grazing [143]. Light to moderate grazing has been shown to improve SOC and soil structure significantly more than heavy grazing [144,145]. The effect of grazing intensity (GI) on extensively managed grasslands in various environments is poorly understood. A meta-analysis of 83 studies from around the world found that the impact of GI on SOC varied by climate zone and grass type, implying that grazing intensity should be optimised based on the regional climate [146]. A combination of improved grazing and biodiversity management practices can lead to a substantial amount of accumulated SOC in soil [147]. Similarly, a recent large-scale survey conducted across six continents demonstrated that the intricate connection between grazing intensity and climate in drylands drives rates of carbon storage, organic matter deposition, and erosion [148].

2.2. SOM-Mediated Improvement of Soil Moisture/Water Uptake

SOM is well known for its functional benefits, including increased soil water holding capacity (SWHC). However, reports on the role of SOC in increasing SWHC are inconsistent. Some studies have found little effect [149,150] or no effect [151,152], while others have found significant effects of increased SOC on soil WHC [153]. Most researchers associate this property with soil texture. An increase in SOM was found to increase soil field capacity (FC) more quickly in sand and silt loam croplands in the midwestern United States [154]. Based on a meta-analysis, Rawls et al. [155] proposed that sandy soils were more sensitive to changes in SOM at a low organic carbon content. Increasing soil carbon was shown to increase soil water retention in sandy soils and decrease it in clayey soils. Interestingly, with high SOC, all soil types increased water retention as SOC increased.

Organic carbon has a favourable effect on soil water holding capacity, but the forms of carbon responsible for this effect, as well as their synergistic behaviour with other soil features, remain unknown [154]. According to Jong et al. [156], increased SOM/SOC is associated with increased soil water content. At field capacity, 1% SOM added 1.5% more moisture by volume [157,158]. Emerson and McGary [159] reported that a gram of extra carbon resulted in a 50% increase in water due to the binding of soil particles with organic carbon exudates from ectotrophic mycorrhiza, which resulted in a change in pore size and water retention at 10 kPa suction.

According to a recent study, while an increase in available water holding capacity (AWHC) was more prominent in sandy soils, a 1% increase in SOM increased AWHC by up to 1.5% depending on soil texture and mineralogy [160]. Minasny and McBratney [161] concluded that increasing SOC had a minor effect on soil water retention, and a 1% increase in SOC caused a 1.16% volumetric increase in water retention. Sandy soils were more responsive to increased SOC, whereas clayey soils showed no effect. Some researchers contend that increasing SOC through simple changes in management practices can increase SWHC; however, such improvement is limited by soil type [162,163]. In sandy soil, for example, a 1% increase in SOC had a significant impact on SWHC [164]. Currently, no SOM threshold has been established due to diverse soils, different growing conditions and management practices, and different types and levels of land degradation. However, Oldfield et al. [165] recently defined an SOM threshold (up to 5%) associated with increased wheat productivity under controlled greenhouse conditions, implying that developing optimal SOM targets is critical for improving water retention and soil fertility.

A variety of factors influence soil water holding capacity, including soil bulk density, infiltration rate, and crop residues. Soil aggregation, porosity, and infiltration rates can be improved by soil fauna and retaining residues on the soil surface [166–168]. Calegari et al. [169] demonstrated that better physical characteristics, conferred by crop rotation

and no tillage, boosted soil water infiltration from 20 mm/h with conventional tillage to 45 mm/h with no tillage (soybean–wheat system). Increased water infiltration combined with increased organic matter content has a positive impact on soil water storage, and mixing organic matter with soil mineral content significantly improves the water holding capacity of soil. More water can be stored, especially in topsoil, which has a higher organic matter content. A 9-year study involving 17 long-term experiments found that adding organic amendments improved available water and soil properties, and the quality of organic C was an important factor [170]. Li et al. [171] recently studied the benefits of earthworm casts on soil water retention and other properties and concluded that the use of small earthworm particles improved soil water retention and decreased soil evaporation. Earthworms were found to increase the percentage of water stable aggregates and water holding capacity, but the amount varied depending on the earthworm species [172]. Another study found that combining corn straw with chemical fertiliser increased the soil water storage capacity of aeolian sandy soil [173]. Reduced aggregate stability due to decreased SOC can reduce soil water retention [174]. Cropping practices that increase soil organic carbon increase the soil's capacity to store moisture [175].

2.3. Increased Soil Biodiversity and Microbial Function

Soil biodiversity, which covers a wide range of living organisms, including microbes and meso-, macro-, and megafauna, plays an important role in ecosystem functioning due to their complex interactions [176,177]. RA practices emphasise improving the functionality of soil microbes in order to reclaim degraded soil fertility (70% globally), grow the healthiest, most nutritious food possible, and combat climate change [178]. The soil microbiota is essential for organic matter breakdown, nutrient cycling, and soil fertilisation [19,179]. Soil microbes are also essential for the growth of a healthy soil structure. Soil resilience is an excellent indicator of an ecosystem's overall functioning. Soils with higher microbial diversity are more resistant and resilient to disturbances than soils with lower microbial diversity [180].

Prior to the development of next-generation sequencing techniques, the soil microbial community was described as a “black box” [181–183]. Understanding the structure of microbial communities is critical for unravelling microbe-driven biogeochemical cycles. It is now widely acknowledged that functional diversity patterns, rather than taxonomic richness, may allow more robust testing of biodiversity theories [184]. However, challenges in characterising microbial function remain due to the lack of a suitable methodology for distinguishing microbial functions, as most studies to date have focused on community structure rather than function. New tools such as meta-transcriptomics/metabolomics will improve our understanding of microbial functions in diverse ecosystems.

Microorganisms account for 80–90% of total soil metabolism and therefore are essential in the biochemical transformation of organic matter and nutrient bioavailability [185]. In temperate grasslands, 1–5% of C and N in soil is stored in living microbial biomass, which is estimated to be 1–2 t ha⁻¹ [180,186]. Plant-associated microbiota are well known for their ability to mobilise nutrients that are not readily available to plants, such as inorganic phosphate and iron, through solubilisation, mineralisation, or excretion via iron-chelating siderophores [187].

Agricultural intensification is one of the leading causes of soil biodiversity loss and reduced food-web complexity among the various human-induced changes [188–190]. Several soil microbiological parameters, such as microbial biomass carbon, extracellular enzymes, fungi-to-bacteria ratio (F:B), and basal respiration rate, have been proposed as potential indicators of soil quality [191]. Intensively managed farmed soils frequently have a lower F:B biomass ratio compared to more extensively managed soils. This phenomenon is thought to be due to tillage, high rates of fertilisation, and a lower C:N ratio favouring bacteria [192,193]. Because fungi have a higher C:N ratio and produce complex enzymes to break down lignin, they have greater potential to sequester carbon. Lower fungal biomass and ratio are generally associated with lower soil C sequestration capacity [194,195].

2.3.1. Role of Microbes in Stable Organic Carbon Fraction

It is widely assumed that plant-derived C accounts for the majority of stable carbon fractions. Living microbial biomass accounts for 5% of SOC, resulting in a minimal contribution to sequestered carbon [196,197]. Microbes, however, have been shown to play an important role in sequestering C into stable soil C pools [198,199]. There is mounting evidence that microbial necromass contributes significantly to soil stable organic carbon. A recent meta-analysis of 148 peer-reviewed journal articles concluded that microbial necromass contributes nearly half of the SOC in croplands, which is stimulated by temperature and soil pH [200]. One of the parameters used in modelling long-term SOC storage is microbial carbon use efficiency (CUE), with high and low CUE indicating the increased and decreased C sequestration potential of soil, respectively [193]. Plant species richness has been associated with rapid microbial development and turnover, resulting in more necromass and higher SOC [201]. Kallenbach et al. [202] used a model soil system to demonstrate that soil microbes produce stable and chemically varied SOM by utilising simple C substrates. While the effect was more pronounced in soils with higher fungal abundance, clay mineralogy had no effect on SOM accumulation and stabilisation. Microbial necromass has been shown to contribute more than 50% of total SOC in temperate agriculture topsoil, implying that good management practices that promote microbial biomass are critical for maintaining healthy soils [203]. However, due to the limitations of current SOM estimation methods, the relative contributions of plant- and microbe-derived recalcitrant carbon fractions are debatable [204]. Microbial biomass and necromass appear to be key factors in regulating soil carbon storage; however, the mechanism of necromass carbon stabilising to stable soil carbon is not fully understood [205].

2.3.2. Nutrient Cycling and Acquisition

Microbial CUE is important to C cycling. Soil microbial community structure and biodiversity have been linked to a variety of important functions in agricultural systems, including plant productivity, C and N cycling regulation, and positive effects on livestock production and yield [18,206,207]. C and nutrient cycling are heavily reliant on microbial communities and are influenced by both biotic and abiotic factors, which can have either positive or negative consequences [208,209]. Abiotic factors such as precipitation and soil moisture can alter the bacteria–fungi ratio and decomposition of organic matter [210].

The majority of nutrients in SOM are derived from mineralisation and become available to plants during decomposition [158]. Mycorrhizal fungi have been well recognised for their role in C, N, and P cycling. Arbuscular mycorrhizal fungi (AMF) have been shown to contribute significantly to Zn uptake in cereals, and the mycorrhizal pathway of Zn uptake is dependent on plant species and available soil zinc [211]. Several Australian studies, however, indicate that AMF contribute little to crop nutrition and productivity in Australian cropping zones, possibly due to the low soil temperature (10 °C) in the southern region [212]. The role of microbes in nutrient uptake is further discussed below. Conservation agricultural practices such as minimum tillage and mulching should be encouraged, because they help to establish AMF communities and the associated agroecosystem services, whereas inorganic fertilisation inhibits AMF colonisation. Mulching and minimum tillage were found to increase maize root colonisation, which increased the uptake of more P and N from the soil, resulting in better maize growth [213].

Nitrogen

Nitrogen is the most important macronutrient for food crop production. In croplands, 90–95% of N is bound to organic matter, with the remainder available as ammonium, nitrate, or nitrite. N is a component of nucleic acids and proteins, and is involved in a variety of plant metabolic processes. N deficiency in crops can result from losses due to leaching, volatilisation, surface runoff, denitrification, and the plant canopy, although N is usually supplied in sufficient quantities to compensate for such losses. Nitrogen mineralisation is a complex process involving diverse microorganisms (bacteria, fungi, and actinomycetes)

that produce nitrates from various substrates such as plant residues, humus, microbial necromass, and manure. However, the rate of mineralisation varies depending on soil type, SOM, crop residue type, microbial communities, and environmental and climatic factors in different fields. Recently, it has been hypothesised that global soil microbial biomass, total nitrogen, and mean annual precipitation all have a positive impact on N mineralisation, indicating the importance of microbes in determining N availability [214].

1. N₂-Fixing Bacteria

Biological nitrogen fixation (BNF) is the first step in the nitrogen cycle, in which a special class of N-fixing bacteria convert atmospheric N₂ into usable compounds. The role of nitrogen-fixing organisms (rhizobia) in symbiosis with leguminous plants is well understood. Biological nitrogen fixation is carried out by various groups of bacteria, archaea, and some fungal and algal species [215]. A symbiotic relationship exists between leguminous plants and N₂-fixing bacteria in biological N₂ fixation. Through photosynthesis, legumes provide energy and carbon to rhizobia, and rhizobia provide nitrogen to hosts in the form of ammonium [216]. Rhizobacteria colonise host plant roots by responding to root exudates via chemotaxis. Grain and forage legumes are frequently used in sustainable farming systems to correct N fertility issues if crop residues are incorporated into the soil after harvest [217,218]. The environment has a significant impact on the efficiency of biological N fixation. High temperature, water stress, and soil acidity/salinity all have a negative impact on the BNF process. A recent meta-analysis found that elevated temperature and precipitation affected BNF in mid- to high-altitude biomes in response to nutrient enrichment [219]. To address the environmental concerns associated with BNF efficiency, management practices such as no or minimal tillage and cover crops are recommended [220,221].

2. Free-Living N₂-Fixing Bacteria

There are some free-living organisms in the soil that fix nitrogen from the atmosphere. The presence of free-living N₂ fixation (FLNF) bacteria is dependent on the availability of C from root exudates, which is required for the energy demands of N₂ fixation [222]. While diazotrophs achieve nearly 80% of biological nitrogen fixation (BNF) in symbiosis with legumes, free-living soil bacteria (e.g., *Pseudomonas*, *Azospirillum*, and *Azotobacter*) can fix considerable amounts of nitrogen (0 to 60 kg N ha⁻¹ year⁻¹), particularly under organic crop production [223]. In general, symbiotic nitrogen fixers fix more nitrogen than free-living and associative nitrogen fixers [224].

FLNF bacteria are common in agricultural soils in Southern Australia. Populations are generally higher in clay soils than sandy soils, and they predominate in cereal paddocks. Significant N fixation occurs in areas of NSW with significant summer rainfall; however, low summer soil moisture (such as in WA) limits FLNF populations [225]. In tropical forests, free-living N fixation was found to be suppressed by N fertilisation and stimulated by Mo fertilisation and P additions, implying that nutrient limitation of free-living N fixation is a common phenomenon [226]. FLNF bacteria and phosphate-solubilizing bacteria isolated from the cotton rhizosphere were found to increase cotton growth by producing plant-growth-promoting hormones [227]. Gupta and Roper (2010) [228] concluded that the ability of aggregates to provide protection against biocidal exposure within the soil matrix was related to the survival of FLNF bacteria in different soils.

Kennedy et al. [229] reported that FLNF bacteria improved plant growth and yield in a variety of Australian field crops by increasing N supply in the soil, consequently reducing the need for fertiliser application. FLNF organisms have recently gained prominence in arid climates due to their role in soil development. FLNF bacteria and some archaea species, in particular, have been found to carry nifH genes from the rhizospheres of plants growing in harsh conditions such as extreme water stress, extreme temperature, high salinity, and low-nutrient deserts [230–232]. Recently, two strains of free-living diazotrophic bacteria were isolated from salt-affected soils of Syria that may have potential for the development of novel biotechnological products for dryland agriculture [233]. Some summer-active

perennial grasses growing in low-fertility sandy soils in Southern Australia's Mediterranean region have been shown to support FLNF diazotrophs in the plant rhizosphere, leaves, and roots, with N-fixing potential ranging from 0.5 to 4 mg N/kg/day [234].

Non-symbiotic nitrogen fixation is likely to be greater with the use of NT practices than in cultivated soils due to the aggregate stability under no-till, which is required for maintaining low oxygen tension and protecting against microcidal exposure [228,235,236]. Crop rotation and stubble retention are two other management strategies that can promote non-symbiotic nitrogen fixation, whereas certain fungicides and herbicides, particularly glyphosate, can harm non-symbiotic nitrogen-fixing bacteria. Certain crop cultivars are genetically superior in their interactions with N-fixing bacteria [237]. The technology for the use of non-symbiotic inoculations may become available in the future, and could potentially reduce the input of synthetic fertilisers. Significant research is being conducted to develop biological N fixation in cereals. Although N-fixing bacteria have been isolated from some cereal crops, the amount of nitrogen obtained was insufficient to meet the needs of the plant and did not match that obtained with chemical fertilisers [238]. Developing cereal crops for nitrogen fixation requires a greater understanding of the microbial traits that promote plant colonisation, persistence, and competitiveness.

Phosphorus (P)

Phosphorus (P) is an essential element for plant growth. As an important component of phospholipids and nucleic acids, it plays a major role in various plant biochemical processes, including energy transfer, photosynthesis, reproduction, and nodule development in legumes. Despite P being abundant, P deficiency is common in soils all over the world due to the low concentration of readily available P in the form of orthophosphate [239]. Plant–microorganism interactions enhance the uptake of available P or access to previously unavailable P sources in P-deficient conditions. AMF, as well as a variety of bacteria and fungi, can solubilise insoluble mineral phosphate complexes, including calcium phosphate complexes. P-solubilizing bacteria and fungi account for 1–50% and 0.1–0.5%, respectively, of the total microbial population in soil, thus P-solubilizing bacteria outnumber P-solubilizing fungi by a factor of 2–150 [240–242].

The role of AMF in increasing P availability in plants is well established [243,244]. Mycorrhizal fungi have been shown to be responsible for up to 75% of plant P acquisition on an annual basis [245]. Extensive research has been conducted on the solubilization of mineral phosphates by microorganisms other than AMF, and the rate of mineralisation varies depending on the soil type [246,247]. Several bacterial genera, including *Pseudomonas*, *Burkholderia*, *Bacillus*, *Rhizobia*, and *Micrococcus*, have the capacity to solubilise inorganic P [248]. Many soil fungi, such as *Penicillium*, *Trichoderma*, and *Aspergillus*, can solubilise insoluble phosphates or help plants acquire P and are thus used in commercial formulations. The mechanisms of microbial P solubilisation include chelation, organic acid production, proton extrusion, exopolysaccharide production, and siderophore and enzyme production and depend on the fungal isolates and types of P sources used [249,250]. Fungi are thought to be more effective than bacteria at solubilising inorganic phosphate because they can move more freely through the soil and release a variety of organic acids [251].

Potassium (K)

Potassium is the third essential element for plant growth and development. It regulates several plant functions, in particular stomatal movement. It plays an important role in pathogen suppression and drought tolerance. Because of its insoluble form, K is generally unavailable to plants in most agricultural soils, resulting in K deficiency. Aside from using K-based fertilisers, introducing certain microbes can facilitate K uptake through K mineralisation. Several K-solubilizing bacterial (*Bacillus*, *Acidithiobacillus*, *Pseudomonas*, and *Burkholderia*) and fungal (*Aspergillus*, *Glomus*, and *Penicillium*) genera have been shown to solubilise K and make it available to plants [252].

Sulphur (S)

The majority of sulphur in soil is bound to organic molecules, with only a small fraction of total sulphur available for plant uptake in the form of inorganic sulphate. Consequently, sulphur deficiency is commonly observed in crop species. Several bacteria, prokaryotes, and fungi are known to oxidise elemental sulphur to form sulphates that can be readily used by plants [253,254]. Some crop plants, such as canola, have high requirements for sulphur. To alleviate sulphur deficiency in canola, some microbial formulations are applied with elemental sulphur [255].

3. Pest, Pathogen, and Weed Control/Suppression

Crop pathogens/pests/weeds cause significant production and economic losses worldwide. Climate change is likely to exacerbate the occurrence and severity of certain diseases and pests, particularly those that thrive in warmer climates. Elevated temperature and CO₂, humidity, and nutritional status all have an impact on plant immune responses [256–259]. Certain agricultural practices, such as monocultures, promote pests and disease. To reduce subsequent losses, integrated disease and pest management is frequently recommended. Traditional plant disease/pest control using fungicides/insecticides is one of the recommended strategies, but it has several limitations. Pesticide overuse in recent years has resulted in pesticide resistance, in addition to pollution and negative effects on soil microbiota. Consequently, there is worldwide interest among researchers in developing environmentally safe and sustainable disease control solutions.

Several soil-borne microbes, including bacteria and fungi, have been identified as pest and disease suppressors. Microbial biological control agents protect crops from pathogens through a variety of mechanisms, including competition, hyperparasitism, and antibiosis. Several beneficial soil bacteria, fungi, viruses, and microfauna have been reported as potential candidates for biological control and ecological balance restoration [260]. Babikova et al. [261] discovered that mycorrhizal fungi, via their mycorrhizal network, can transmit defence signals from aphid-attacked plants to unaffected plants, providing an early warning to intact plants. Manipulating plant microbiomes to make plants more resilient to pests and diseases has recently gained traction. However, because the research is still in its early stages, a collaborative cross-disciplinary effort is required to develop and realise the full potential of this technology in diverse farming systems. There is evidence that management practices such as reduced tillage, intercropping, cover cropping, and the use of organic fertilisers increase predatory and beneficial insects, thereby providing natural pest control [262–265].

Weeds are a serious problem in WA farming systems, and chemical weed control is heavily used. Weed control in no-till and other regenerative farming practices will be extremely difficult unless new non-chemical methods are developed quickly. In Europe, research is being conducted to find sustainable non-chemical solutions for weed control in arable crops [266]. Chemical weed control is not only expensive, but it also has serious issues in terms of weed species developing resistant populations. Integrated weed management (IWM), which combines physical, cultural, genetic, biological, and chemical approaches, is the way forwards for long-term weed control.

Allelopathy is another approach that could be used to reduce weedicide use. Soil microbes such as fungi, bacteria, viruses, and nematodes have the ability to reduce the weed seed bank [267,268]. However, one of the major drawbacks of using microbes for weed control is that the majority of microbes are pathogens common to both weeds and crop plants. Furthermore, inconsistencies in field efficacy and product maintenance are significant barriers to developing bio-herbicides [268]. Due to their early vigour, crop varieties with enhanced weed-competitiveness traits have a chance of being developed. Some wheat cultivars with such characteristics can help reduce weed populations and the need for chemical applications [269–271]. Recently, a new technology for post-emergence weed control in cereals has been developed by combining digital image analysis with automatic harrowing intensity adjustment [272].

4. Mechanisms Involved in Improved Microbial Functions

4.1. Liquid Carbon Pathway

Proponents of RA have suggested that the liquid carbon pathway (LCP) comprises a 420 million-year-old symbiotic relationship between mycorrhizal fungi and 90% of all plants. Plants produce excess carbohydrates (simple plant sugars), which they exude into the soil to feed the fungi. In exchange, mycorrhizal fungi mine and transport nutrients and water back to their host. AMF can gain access to nutrients and water that larger plant roots cannot. The liquid carbon pathway is regarded as the primary mechanism of long-term soil carbon sequestration. According to RA advocates, pasture soils with healthy LCP associations increase the amount of carbon sequestered beneath the grass every year. Some pastures are currently sequestering up to 32 tonnes of CO₂ per hectare per year. This is due to glomalin-related soil protein (GRSP), which is produced in the hyphal cell walls of mycorrhizal fungi and acts as a carbon storehouse, influencing aggregate formation and stabilisation and contributing to soil carbon sequestration [273,274]. Another study found that roots and rhizodeposition products are highly efficient C sources for the formation of particulate- and mineral-associated organic carbon [275]. This study also suggested that SOC in degraded croplands can be effectively increased by including plants with higher C allocation to below-ground biomass.

Our understanding of the importance of microbes in carbon sequestration is growing. Liang et al. [199] proposed a microbial carbon pump (MCP), a conceptual framework for demonstrating soil C storage mechanisms by microorganisms. According to this model, microbes actively pump carbon into the soil via the metabolic processing and deposition of microbial necromass into stable C fractions. Zhu et al. [276] recently demonstrated that microbial necromass was the dominant contributor to recently accumulated SOC in perennial energy crops, implying that diverse perennial crops are important in stimulating soil MCP.

Root exudates play a key role in shaping microbial communities in the rhizosphere, and the rate of root exudation is influenced by the presence of microbes in the rhizosphere [277]. In young seedlings, the transfer of photosynthates to below-ground components, including the rhizosphere and roots, ranges from 20–50% [278]. Using isotope tracer studies, Villarino et al. [275] demonstrated that rhizodeposition was highly efficient in the formation of mineral-associated organic carbon (46%) compared to below- and above-ground plant inputs, whereas root biomass contributed 19% to the formation of particulate organic matter (POC), suggesting that growing plants with higher exudation may increase C stocks. Root exudates are also known to stimulate some soil-borne fungi and can thus negatively impact plant production [279]. However, root exudates recruit beneficial microorganisms that provide robust plant protection and counteract the negative effects of pathogens [280,281].

4.2. Improved Uptake of Water

The highly branched hyphae of AMF are about 2 µm in diameter, can move through soil particles less than 30 µm in diameter, and can access water in either an active or passive manner [282]. AM fungi facilitate water uptake through a variety of mechanisms, including changes in soil properties, stomatal conductance, and hydraulic conductance. However, the role of hyphae in water uptake is still debated, with some studies supporting their contribution and others claiming that they play a minor role [283]. Under limited moisture conditions, the roots of AM plants can increase apoplastic water flow and switch between different water transport pathways [284]. Kaya et al. [285] and Ruiz-Lozano and Aroca (2010) [286] reported increased water use efficiency due to mycorrhiza. The number of external hyphae and the frequency of root colonisation have been linked to water uptake efficiency of AM fungi [287]. Kakouridis et al. [288] recently demonstrated that water transport by AM fungi is extra cytoplasmic, and their results indicated that AM fungi accounted for 46.2% of the water transpired by AM plants.

4.2.1. Drought Tolerance

Declining rainfall due to climate change is having an adverse impact on crop productivity world-wide. Breeding for drought tolerance is the key to reducing this impact; however, breeding programs are complex and it may take several years before drought-resistant/-tolerant crop varieties become commercially available. Furthermore, plant fitness responses to drought have been linked to changes in below-ground microbial communities rather than plant trait evolution [289]. There is growing interest in using plant-associated microbial communities to manage various abiotic stresses in crops, including drought tolerance. Drought causes the reshaping of plant-associated microbiomes, which benefits plants by allowing them to better cope with moisture stress conditions [290].

Currently, studies are being conducted to assess the ability of plant-associated microbiomes to alleviate drought stress in agricultural crops [291]. Drought induced the enrichment of Actinobacteria in a grassland biome, and these bacteria are more abundant in the root endosphere than in the surrounding soil under drought conditions [292]. Plant growth promoting rhizobacteria (PGPR) have also been linked to increased drought tolerance in plants under water stress conditions [293–296]. Drought-tolerant microbial consortia (mixtures of beneficial bacteria and AM fungi) are likely to provide a solution to drought stress in the face of climate change [297]. AM fungi have been shown to improve plant drought tolerance by improving osmotic adjustments in the roots, thus increasing the water potential of the leaves [298,299]. Drought tolerance in rice and maize by AM fungi is attributed to the increased AMF colonisation and conversion of putrescine to γ amino butyric acid, respectively [300,301].

4.2.2. Nutrient Uptake

The interaction of plant roots and soil microorganisms influences nutrient availability and uptake [302–304]. Factors that improve P and N nutrient acquisition are highly desirable for plant growth and development. Certain root characteristics, such as root elongation, high root-to-shoot biomass, increased root branching and angle, root hair and proteoid roots contribute to P uptake [305–307]. A rhizophagy cycle is proposed for nutrient acquisition in plant roots by symbiotic bacteria and fungi, in which plant nutrients captured by microbes are released into the roots via an oxidative process [308]. Root exudates are essential for making P available to plants and increasing microbial activity [309].

Microbial-mediated plant growth has been attributed to hormonal signalling in plants, outcompeting pathogenic strains and increasing the bioavailability of soil nutrients [310]. Several microbial processes depolymerise and mineralise organic N, P, and S, and release their inorganic forms into the soil [245]. The flavonoid pathway, via root exudates, is important in legume rhizobia-mediated N fixation [310]. Furthermore, flavonoids have been linked to hyphal branching and, as a result, improved nutrient uptake by mycorrhizal fungi [311,312]. According to some metagenomics studies, certain microbial genes are more abundant in soils with lower fertiliser inputs [313]. However, little is known about which specific microbial strains contribute significantly to plant nutrition and which do not.

Plant growth can be hindered by a lack of nutrients. Because the crops grown in WA farming systems require high soil fertility, high doses of fertilisers are applied to meet their nutritional demand. Nutrient uptake by plant roots in nutrient-deficient soil is generally thought to be low [314] and is more pronounced in the rhizosphere than in the outside zone [302].

4.2.3. Role of Soil Microbes in Enhanced Aggregates, Plant Growth, and Photosynthesis

Soil structure is central to crop management and sustainable crop production. Sand, silt, and clay particles of varying sizes combine to form micro- (250 μm) and macro- (>250 μm diameter) aggregates. It is surmised that soil microbes, including bacteria and fungi, influence aggregate formation by producing extracellular polysaccharides that bind soil particles [315]. Microbial community structure is thought to play an important role in the formation of different aggregate types. Certain soil bacterial taxa (e.g., *Rubrobacteria*)

have been shown to have a high correlation with macro-aggregates [316]. Two main mechanisms by which fungi help form soil aggregates are suggested [317]. In the direct mechanism, fungal hyphae entrap soil particles and force them together. In the indirect mechanism, AM fungi produce glomalin and other fungi and bacteria produce mucilage and polysaccharides that bind the soil particles to form aggregates. In a study by Tang et al. [318], fungi were found to form large aggregates, and fungicide application reduced aggregate stability hence confirming the role of fungi in aggregate formation. There is little information on the mechanisms underlying root-exudate-mediated C dynamics and their effects on root aggregation at different depths. Under artificial experimental conditions, the addition of more exudates resulted in a shift in the microbial community in favour of fungi that promoted macro-aggregates, with a notable effect in C-deficient soils [319]. Rillig et al. [320] proposed that glomalin may play an important role in the hyphal-mediated process of soil aggregate stabilisation for a water-stable aggregate size of 1–2 mm.

To improve plant growth under biotic and abiotic stress conditions, soil microbes use a variety of molecular and physiological mechanisms. PGPR facilitate plant growth by regulating various growth hormones or improving nutrient availability and acquisition. Such beneficial effects are thought to be more pronounced in plants growing in poor soil conditions [321]. To suppress crop pathogens, some PGPR produce volatile organic compounds (VOCs) and other antimicrobial compounds, such as hydrogen cyanide (HCN) [322,323]. The inhibition of cytochrome c oxidase and other metalloenzymes involved in respiration and other cellular processes is attributed to HCN's toxicity in terms of suppressing plant pathogens [324]. Endophytic microbes residing in plant roots influence plant growth by sending chemical signals to above-ground plant parts [325].

Under physiological stress conditions, reactive oxygen species (ROS) damage the photosynthetic capacity of crop plants. Several researchers are looking into the role of microbes in enhancing photosynthesis under stress conditions. AM fungi were found to inhibit chlorophyll loss in watermelon under water-stress conditions [326]. Likewise, other endophytic genera, including *Piriformospora* and *Trichoderma*, have been reported to reduce the loss of photosynthetic capacity of crop plants during salinity stress and pathogen infection. Some phosphate-solubilising bacteria have been shown to increase photosynthetic capacity in *Camelina oleifera* and rice [327,328].

5. Effect of Management Practices on Microbial Activity

Agriculture intensification reduces the functional groups of soil biota and jeopardises soil functions, reducing agricultural productivity [329]. Conservation agricultural practices such as crop rotation, manuring, reduced tillage, and cover crops improve or maintain soil quality for sustainable crop production by regulating microbial communities [330,331]. Nutrient management and long crop rotations, however, may have a direct impact on community structure and the associated ecosystem services across croplands [331].

Crop rotations that include cover crops and incorporate organic amendments improve soil fertility by increasing soil C, N, and microbial biomass, benefiting agroecosystems in the longer term. One of the most serious consequences of reduced crop rotation is the loss of biodiversity. A meta-analysis of 122 studies on the effects of crop rotation on soil biological properties found that rotation significantly increased the soil microbial biomass C and N by 20.7 and 26.1%, respectively [78]. Some research has found that diversified crop rotation improves plant resource use efficiency by increasing microbial functions [332].

When cover cropping is combined with other agricultural practices, the soil microbiome can become more robust [333]. Combining crop residues from mixed species and monocultures with agricultural soil was shown to stimulate microbial diversity and function, and the nutrient content of the cover crops was indicated as the main driver of nutrient release [334]. Diverse cover crops have been shown to increase microbial activity in sandy soils, with a long-term positive impact on yield [335]. It has been demonstrated in several studies that cover crops increase microbial biomass and enzyme activity [179,336–338]. However, Kim et al. [333] cautioned that the increased microbial activity could be due to in-

creased microbial abundance or an increased per capita enzyme production rate. In contrast, some studies found no strong relationship between species diversity and ecosystem functions [339,340]. Because specific cover crop species can increase the abundance of particular microbial groups [179], different combinations of species can be used to tailor the microbial community composition in order to achieve the desired microbial functions [341]. Diversified catch crop mixtures were found to improve cropping system, C cycling efficiency and have a positive impact on microbial abundance, activity, and diversity [342].

Retention of crop residues significantly increases soil microbial diversity and function [343]. In the low-fertility sandy-loam soils of WA, stubble retention increased microbial biomass, function, and enzyme activity but had no effect on microbial diversity [344]. No-tillage farming practices, combined with crop rotation and residue retention, have been shown to increase microbial biomass and physiological diversity [345]. Soil microorganisms regulate mineralisation and organic matter stability by producing a variety of extracellular enzymes [346]. Cropping practices have varying effects on soil enzyme production; for example, enzyme activity can be increased with no tillage but be unaffected by crop rotation in the short-term [347]. A few studies have found that the use of cover crops increases microbial biomass, extracellular enzyme activity, and glomalin [348]. Continuous application of inorganic fertilisers may be harmful to soil enzyme activity and biological health in the long run [349]. Because of their low C/N ratio, legume cover crops provide a significant amount of biologically fixed N to primary crops and decompose easily.

Increased microbial biomass and activity with various cropping practices has been reported [350–354]. Microbial biomass in no-till soils contain more nutrients than microbial biomass in conventionally tilled soils, implying greater nutrient cycling and fluxes through microbial biomass without tilling [355].

In a Mediterranean climate, the combination of no tillage and liming has been shown to increase mycorrhizal colonisation, N content, and biomass of a mixed oat and vetch crop, possibly due to increased nutrient efficiency via crop–microbe interactions [356]. Reduced tillage, residue retention, and cropping promote higher microbial biomass, while cover cropping has variable effects [357–360]. Tillage generally accelerates crop residue decomposition and organic matter, resulting in decreased overall soil resource quality [359].

A higher fungi-to-bacteria biomass ratio has been linked to quantitative and qualitative improvements in SOM when no-till practices are used [361]. Furthermore, fungal-dominated communities are expected to have a slower rate of C turnover than bacterial-dominated communities due to their higher-efficiency C use. No-till farming systems were found to have higher soil carbon and a higher fungi-to-bacteria ratio compared to conventional farming systems [362]. The transition from direct drilled to conventional or stubble-incorporated practices resulted in a significant decrease in organic C, total N, soil water holding capacity, microbial biomass, and fungi-to-bacteria ratio respiration in the top 0–5 cm of red duplex soils in NSW [363].

5.1. Role of Biofertilisers and Biostimulants

Fertilisers are used in almost all cropping systems to meet the nutrient demands of growing plants. There is increasing concern that excessive fertiliser use is contributing to soil degradation, soil and water pollution, and GHG emissions. Global research efforts are currently focused on developing microbial-based nutrient solutions that can replace synthetic fertilisers and pesticides. Due to growing concerns about the health effects of farm chemicals, the use of biofertilisers and biostimulants in agriculture has gained traction in recent years. Furthermore, consumer demand for clean, safe, and nutrient-dense food is increasing.

Plant biostimulants derived from natural materials are thought to be environmentally friendly and innovative alternatives to chemicals/inorganic fertilisers for increasing crop production by modifying physiological processes such as nutrient use efficiency and tolerance to abiotic and biotic stresses [364,365]. While there is no agreement on the definition of “biostimulants”, the EU recently defined the term according to specific agricultural

functions involving various natural compounds such as humic and fulvic acid, plant- and animal-derived hydrolysates, seaweed extracts, silicon, and microorganisms such as AM fungi and N-fixing bacteria [365]. The term “biological amendments” encompasses biostimulants, organic amendments, biological inocula, and composts [366].

Beneficial microbes are of particular importance and will almost certainly play a significant role in revolutionising agriculture over the next several decades. There is now a significant resurgence of interest in developing microbial-based agricultural products, and all of the major agribiotech companies are investing in the development of biological applications. According to a recent Meticulous Research report [367], the global biopesticide market is expected to grow at a compound annual growth rate of 16.1% from 2019 to 2025, reaching USD 10.24 billion. Significant research efforts are being directed towards developing environmentally friendly biocontrol strategies for crop disease and pest management. There are also numerous scientific publications that describe the roles of various soil and aerial microbes in promoting plant growth, facilitating/improving nutrient acquisition by plants, and providing tolerance to moisture stress, salinity, and various pests and diseases. The effectiveness of a biostimulant is determined by the type of biostimulant and the crop. A recent greenhouse study reported that marine and fungal biostimulants increased grain biomass and positively impacted grain protein in durum wheat [368].

There are around 21 commercially available rhizobacterial-based plant-growth-promoting products for horticultural and field crops, including cereals, in various parts of the world [74]. In Australia, a biostimulant coating called Ferticoat™ has recently been developed to improve fertiliser use efficiency. This product can be mixed with UAN or applied with granular fertiliser. Certain biostimulants have been shown to improve food nutritional quality, especially in horticultural crops [369]. The use of an amino acid biostimulant was reported to increase soybean yield and antioxidant potential [370]. Similarly, in winter wheat, some amino-acid-based biostimulants have been shown to increase nutrient content, particularly copper (31–50%), sodium (35–43%), calcium (4.3–7.9%), and molybdenum (3.9–16%) [371]. Zinc foliar spray combined with the biostimulant fulvic acid increased grain Zn content in wheat grains by 16% [372]. The demand for biostimulants will rise in the future, but significant field-based research is required to test these products at multiple scales and develop effective formulations for wide-scale adoption of this technology.

It is uncertain whether RA can supply appropriate plant nutrition while substituting or reducing the need for synthetic inputs. However, research shows that some management strategies, such as no-till, cover crops, crop rotation, and perennial crops, boost SOC, microbial activity, and nutrient cycling. Soils with SOC as low as 1% contain considerable amounts of nitrogen and other nutrients and may offer a sufficient supply if they become accessible to plants. Furthermore, because of its high cation exchange capacity (CEC), SOC improves soil nutrient retention [373].

5.2. Effect of Synthetic Inputs on Soil Microbial Activity

Some pesticides used for crop protection have an impact on soil chemical and biological fertility, with numerous potential negative effects on soil microorganisms, including non-target species [374–376]. Broad-spectrum fungicides are toxic to most fungi and result in a decline in the beneficial types [377]. Some foliar fungicides reduce non-target microbial community structure and functionality in the short-term [378]. The fungicides azoxystrobin and pyraclostrobin were shown to reduce microbial richness and biodiversity [379,380]. Fungicide use may also have an effect on the foliar microbial community. According to Katsoula et al. [381], repeated use of iprodione may affect both epiphytic and soil microbial communities, potentially affecting the yield and quality of agricultural produce. Repeated use of the fungicide chlorothalonil has been shown to have a detrimental effect on microbial respiration, dehydrogenase activity, and microbial community structure under greenhouse conditions [382]. Among the fungicides, carbendazim, mancozeb, captan, metalaxyl, fludioxonil, thiram, and trifloxystrobin have been reported to decrease soil microbial biomass and AMF [383–385]. Topsin, another fungicide, was found to reduce

AMF colonisation and biomass production in *Andropogon gerardii*, a warm-season grass. Despite a reduction in AMF colonisation, the biomass of a cool-season grass, *Pascopyron smithii*, was not reduced [386].

There have been numerous reports of insecticides having a negative impact on soil bacterial and fungal communities. Some insecticides, such as endosulfan, chloropyrifos, and imidacloprid, have been shown to have a negative impact on soil microbes [387,388]. Herbicides, however, have contradictory effects on soil microbes. Glufosinate had no effect on soil bacterial community structure and diversity when applied to glufosinate-tolerant rapeseed plants [389]. Likewise, some herbicides did not have any adverse effects on non-target microorganisms. In contrast, herbicides such as atrazine and metribuzin adversely impact *Bradyrhizobium* populations [390].

Intensive fertilisation is thought to harm soil microbes, and in particular AMF diversity and abundance, and changes interactions between below- and above-ground plant communities due to changes in soil chemical properties [391,392]. The effects of N fertilisation on AMF, however, are debatable. Some studies have found that large amounts of N fertilisation have a suppressive effect on AMF [393,394], while others have found no discernible impact on root colonisation or species diversity [395–398]. High levels of a homogeneous P supply have been shown to strongly suppress AMF colonisation, abundance, and diversity [399,400]. N fertilisation has been linked to soil acidification, with serious consequences for soil organisms [401].

Aside from fertilisation, many other factors, such as N and P availability ratios, [402,403], soil pH [404,405], AMF species [406], soil organic matter content [407], and plant community composition [408], can influence AMF communities in an ecosystem. P treatment was found to briefly inhibit the formation of new arbuscules in AMF [409]. The long-term effects of N and other inorganic fertilisers on plant- and soil-based fungal and bacterial communities are being studied extensively. Nitrogen fertilisers, in particular, reduce the ability of rhizobia to promote plant growth and alter the function of AM fungi by reducing their richness and diversity [410–412]. Huang et al. [413] recently reported that the use of inorganic fertilisers in grassland ecosystems over 150 years reduced the richness and diversity of both plant and soil microbes, and, more importantly, decreased potential associations between plants and functional microbes.

Pesticides have also been shown to inhibit a variety of soil biological processes and enzymes, including hydrolases, oxidoreductases, urease, and dehydrogenase) [414]. Some fungicides temporarily inhibit the C-cycling activity of soil fungi [415]. Mancozeb, chlorothalonil, thiram, and carbendazim are fungicides that inhibit nodulation and nitrogen fixation [416]. Ridomil Gold, however, has been reported to increase N and P mineralisation. A recent European study found that fungicide use and land-use intensification reduce the natural nutrient uptake capacity of AM fungi [417].

6. Nutrient-Dense Food

RA practitioners claim that higher yields have resulted in decreased nutrients in plants, and that adopting RA practices can improve the nutritional quality of food. Climate change, particularly elevated CO₂, can have a negative impact on the nutritional quality of grain [418]. Nutritional security is critical to global food production and is inextricably linked to human health. Soil quality and fertility have a large impact on nutrient levels in food crops. Poor nutrient content in food has been linked to soil depletion of micro- and macronutrients. Soil mineral content has been reported to be depleted by up to 85% in several countries over the last century [419]. Mineral nutrients in fruits and vegetables have been found to be significantly reduced [420,421].

Cunningham et al. (2001) [422] compared the nutrient contents of 44 types of Australian vegetables and fruits and discovered no significant differences in mineral content over time. In another study comparing historical plant and soil samples [423,424], it was found that the decline in mineral content in wheat grains after 1960 was caused by changes in wheat cultivars, whereas the mineral content of soil remained stable or increased due to

the addition of mineral or organic fertilisers. McIntyre et al. [425] proposed that implementing efficient farming systems could improve human nutrition and health. Alternatively, crop species with higher micronutrient contents should be identified and used in breeding programmes to improve the nutritional quality of food crops [426].

Although prevailing climatic conditions can influence food nutrient content, soil type may play an important role in plant nutrient accumulation [427]. In the semi-arid region of Saskatchewan, for example, low protein content in wheat under no till compared to minimum tillage has been reported, whereas no significant difference was observed on sandy loam soil [428]. To date, no scientific studies have been conducted to demonstrate the role of the RA system in improving the nutrient density of arable crops. Certain management strategies, such as the use of appropriate soil amendments and beneficial microorganisms and legume-based crop rotation, are suggested to improve soil health and food nitrogen content [429].

7. Climate Mitigation

According to RA practitioners, one of the co-benefits of RA is reduced greenhouse gas emissions. Australian agriculture accounts for 14.6% of annual GHG emissions, including methane and nitrous oxide from enteric fermentation of livestock/ animals and cropping, respectively. Increased temperature and potential soil erosion can reduce agricultural productivity by 10–20% due to SOC loss [430]. Agricultural soils are thought to be a major C sink, with potential C sequestration of 1.1–2.2 Pg C over the next 50 years [431]. The ability of agricultural practices to mitigate climate change is attributed to SOC sequestration in soil via photosynthesis. Carbon sequestration could potentially offset fossil fuel emissions by 5–15% on an annual basis, with croplands, grazing/ range lands, degraded/ deserted lands, and irrigated soils having the highest sequestration potential [128]. C sequestration in soil is aided by management practices such as the use of perennial forage crops, the elimination of bare fallows, the cultivation of biofuel crops, improved nutrient management, reduced tillage, and the production of high residues [108].

Tiefenbacher et al. [432] recently reviewed the potential C sequestration of agricultural management practices in topsoil. Composting, no tillage, and cover crops have the highest potential for sequestration. The C sequestration potential of mineral N fertilisers is almost neutral, and bare fallow has negative potential due to the loss of carbon stocks. However, the authors cautioned that the benefits of C sequestration must be validated under specific soil and climatic conditions. Climate smart agricultural practices have been advocated in order to increase crop yields, profitability, and resource efficiency and reduce GHG emissions [433]. However, cultural, physical, and economic barriers must be overcome before these practices can be widely adopted. Some researchers believe that the estimation of climate change mitigation by agricultural practices is uncertain because it requires complex and expensive quantification and monitoring technologies [434]. Hence, simple on-farm monitoring tools must be developed [435]. Some analytical and predictive tools have been used to estimate C stocks and sequestration potential [436–438].

The literature on the climate mitigation potential of fully regenerative farming is scarce. In South Carolina, US, investigations revealed a significant increase in SOC at multiple farms that switched from conventional fallowing to regenerative cover cropping practices with limited chemical and N application [439]. Similarly, recent modelling indicates that adopting RA practices could reduce GHG emissions by 14–27% in arable lands in the UK within 30 years [440]. As mentioned in previous sections, some individual RA practices can potentially sequester C in soils, but it is also possible that when these practices are used holistically, they may have a synergistic effect on sequestering C.

Overall, the literature indicates that four-way interactions (plant–microbe–management practices–environment) are the primary drivers of C sequestration, improved soil health, and resilience in an agricultural biome (Figure 2). The scale of RA will be determined by several factors, the most important of which are farmers' well-being and financial feasibility. The financial and social elements of RA are not included here since they are outside the

scope of this review; however, separate studies on the topic have been published [441–443]. The exact level of RA uptake in different areas of the world is difficult to estimate because it differs by location and country. Elements that make RA popular depend on the individual farmer to a large extent, but can include low operating costs (due to reduced inputs), perceived improved soil health, perceived increased soil organic carbon (and associated benefits), producing more nutritious food, and probably a feel-good factor from farming in a more sustainable manner. Another socioeconomic impediment in the uptake of RA is a lack of technical competence and understanding of RA procedures, as well as government policies, market access, and sufficient research on the benefits of RA. Governments, non-governmental organisations, and research organisations can all play an important role in promoting the adoption of regenerative agriculture by providing education and training, enacting policies that support these practises, and assisting in the development of markets for regeneratively grown products [444].

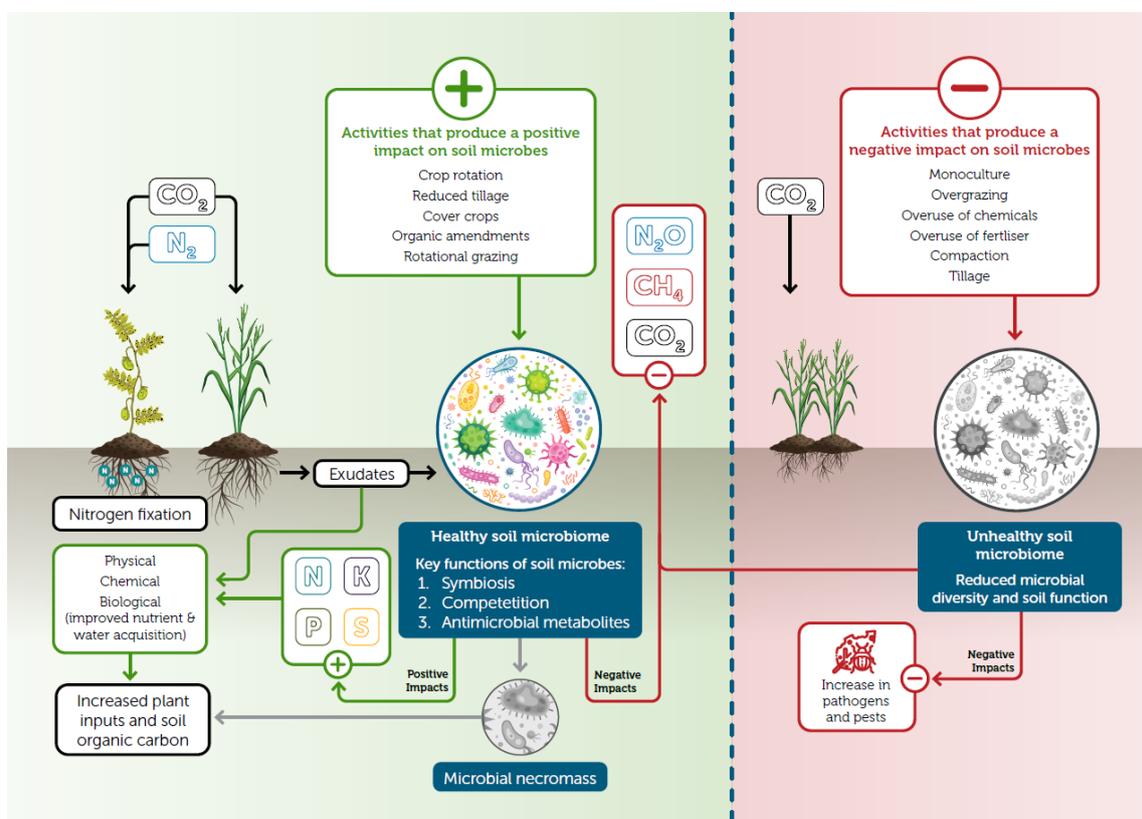


Figure 2. Plant \times microbe \times environment \times management interactions impacting soil organic carbon (SOC) and soil health.

It is acknowledged that switching to RA could result in lower yields in the first few years, but the production losses may be offset by lower input costs. Farmers must be able to generate income to sustain their livelihoods while transitioning to RA. Rattan Lal, a distinguished soil scientist and World Food Prize winner, believes that “if farmers are expected to do things that are useful to the global community and the world, incentivization rather than penalty is the best option”.

8. Conclusions

RA is gaining traction in response to the challenges posed by climate change and rising input costs. The adoption of climate smart agricultural approaches, including RA, is proposed to reduce the impact of extreme weather events and combat GHG emissions. RA is not a completely new farming system; rather, it incorporates features from established

sustainable agricultural systems with the primary goal of restoring soil health in order to revitalise degraded land and bring environmental, economic, and social benefits to a broader community. Furthermore, the system could help in carbon sequestration if the recommended management techniques are followed.

Due to the paucity of empirical research comparing the benefits of a completely regenerated system against the traditional system, this review paints a complicated picture to give an evidence base clearly outlining the pros and cons of implementing this technology. This is due, in part, to the lack of a globally agreed definition of RA, which makes evaluating the purported benefits challenging for researchers. However, there is strong scientific evidence that the individual RA methods discussed in this review have the ability to achieve outcomes such as restored soil health and, to lesser extent, higher yields. One of the most important aspects of RA is improved SOC, which is critical for facilitating nutrient cycling and sustaining both plants and soil inhabitants. The carbon pool in the soil is more than three times higher than that in the atmosphere. Soil carbon has been significantly depleted as a result of land use changes, notably agricultural management systems and soil erosion. Climate change will also have an impact on global carbon reserves. There is compelling scientific evidence that agricultural soils will serve as the largest carbon sink for decades; however, the magnitude of the carbon sequestration capacity is mostly influenced by regional climate and soil types. Combining regenerative farming approaches could boost soil carbon sequestration capacity and soil quality.

SOM and SOC are major drivers of soil biodiversity, regulating a wide range of biological processes in soil, and even a slight decrease in SOC can harm soil health by impeding ecosystem functions. Management practices have a profound effect on shaping microbial communities, thus influencing ecosystem services. Soil biodiversity loss in intensively managed soils is well documented. Agricultural soils in Western Australia are naturally low in SOC, and the potential threat to soil biodiversity is currently very high. The literature shows that sustainable management practices increase microbial biomass, activity, and soil functions. Despite the significant challenges in developing SOC in WA drylands, particularly in areas with limited water availability, the literature suggests that, by adjusting agronomic practices, there is potential for carbon sequestration and enrichment of below-ground biodiversity.

Evidently, the scalability and successful implementation of RA systems will depend on site-specific studies demonstrating their economic viability, as growers are more likely to switch if there are no financial or environmental risks. Consumer demand for food that is safe and produced using environmentally sustainable technologies is undeniably growing. Researchers around the world are working to develop such technologies, and scientific evidence is mounting that various RA practices can potentially help prevent soil degradation, improve soil health, and produce nutritionally rich food in dryland agriculture. However, researchers face a significant challenge in attracting adequate funding to understand, evaluate, and unravel the complexity of RA systems. Extensive research is required to develop regionally specific RA approaches. Soil biodiversity in different agro-ecological zones is poorly understood including Western Australia. Long-term multi-disciplinary research is needed to understand whether RA methods improve soil biological traits and fertiliser efficiency, and thus reduce reliance on synthetic inputs. Government and industry research support is critical to unlocking this potential and developing novel cost-effective regenerative farming technology applicable to Mediterranean climatic conditions, as well as extension programmes that not only increase RA acceptability and implementation but ensure food and nutritional security.

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