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Review

Optimizing Carbon Sequestration in Croplands: A Synthesis

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Abstract: Climate change and ensuring food security for an exponentially growing global human population are the greatest challenges for future agriculture. Improved soil management practices are crucial to tackle these problems by enhancing agro-ecosystem productivity, soil fertility, and carbon sequestration. To meet Paris climate treaty pledges, soil management must address validated approaches for carbon sequestration and stabilization. The present synthesis assesses a range of current and potential future agricultural management practices (AMP) that have an effect on soil organic carbon (SOC) storage and sequestration. Through two strategies—increasing carbon inputs (e.g., enhanced primary production, organic fertilizers) and reducing SOC losses (e.g., reducing soil erosion, managing soil respiration)—AMP can either sequester, up to 714 ± 404 (compost) kg C ha^{-1} y^{-1}, having no distinct impact (mineral fertilization), or even reduce SOC stocks in the topsoil (bare fallow). Overall, the carbon sequestration potential of the subsoil (>40 cm) requires further investigation. Moreover, climate change, permanent soil sealing, consumer behavior in dietary habits and waste production, as well as the socio-economic constraints of farmers (e.g., information exchange, long-term economic profitability) are important factors for implementing new AMPs. This calls for life-cycle assessments of those practices.

Keywords: 4-per-mille initiative; agricultural soil management practices; climate change adaptation; climate change mitigation; long-term experiments; soil organic carbon (SOC) stock; knowledge gaps; trade-offs

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1. Introduction

Terrestrial soils store twice as much carbon as the atmosphere [1–3], with an estimated soil carbon storage of 1462 to 1584 Pg in the upper 100 cm of the soil profile [4]. Historical land-use changes—especially the conversion of grasslands and forests to cropland—as well as crop management practices have provoked a significant decrease in soil organic carbon (SOC) stocks, thus leading to enhanced carbon dioxide (CO_2) emissions to the atmosphere [5]. Combatting climate change requires a reduction in atmospheric CO_2 concentrations, which can be achieved by both reducing CO_2 emissions and increasing carbon sinks [3]. The total organic carbon content of soils is an important soil quality indicator that has an impact on different soil functions—including primary productivity and climate regulation—and ecosystem services, and its loss is one of the soil threats addressed in the Soil Thematic Strategy [6–9].

The 4-per-mille initiative launched by the French Minister of Agriculture at the UN Climate Change Conference (COP21) in Paris (2015) aims to increase SOC stocks by 0.4 percent per year through optimized land and soil management in agricultural soils [10]. SOC stock boosting management measures such as fertilization, diverse crop rotations, cover cropping, and reduced tillage practices have been extensively discussed over the last 20 years and there is agreement that those beneficial practices must be maintained [10–12]. Furthermore, long-term monitoring, at least for more than 10 years, is necessary [10,12,13] to detect changes in SOC stocks. One of the challenges to measure these changes is linked to the uncertainties of sampling or analyzing SOC and of determining soil bulk density [14]. SOC stocks are always a result of soil organic matter (SOM) stabilization and decomposition processes in soil. In the past 10 years, a paradigm shift has occurred, indicating that the biotic and abiotic environment is more important for the persistence of SOM than the qualitative information organic matter contains, including its complexity and composition [15–17]. However, other publications emphasize the enormous importance of structural features and other qualitative information about SOM [6]. The authors of [18] evaluated 20 different fractionation methods and highlight that fractionation of SOC (in fact SOM) is crucial to understand SOM decomposition and stabilization processes. Hence, SOC can be located in different C pools with distinct turnover times, and changes in land use and agricultural management may have different effects on these C pools [19,20]. Labile pools may accumulate much faster but are also more prone to losses than stable pools. The authors of [21] conclude that (energy) crops with high root biomass and high annual root productivity may help enhance physically protected SOC stocks, even if the total stock does not change. Nonetheless, the authors of [15] suggest to focus on a continuum of organic compounds rather than on differentiating between C pools with different turnover times and on the protection of these compounds. Besides agricultural land-use practices, in temperate regions the main explanatory variables for SOC storage are: Soil texture, soil water regime, biological activity, soil C/N ratio, total SOC content, soil pH, climate, vegetation, as well as land-use history of the sites [20].

Climate change along with changes in the soil water regime, the vegetation, or in soil management may further change SOC stocks. In general, higher temperatures and unchanged precipitation patterns increase soil C turnover, which means that a higher proportion of the soil organic matter stocks is converted or mineralized. In order to maintain or increase the current SOC stock, more organic matter must therefore be added (harvest residues, cover crops, field forage), or processes promoting mineralization (soil cultivation) must be reduced [22,23]. Overall, the intensity and type/mode of management practice influence the soil organic carbon stocks of cropland soils [24–26]. Thus, benefits and trade-offs of a certain agricultural management practice should be considered more precisely prior its application. Here, we synthesize the most recent scientific literature regarding the impact of agricultural management practices on cropland SOC stocks. We selected nine management practices that have been extensively studied in long-term agricultural field experiments:

(1) Mineral fertilization
(2) Organic amendments
(3) Crop residues
(4) Plant cultivation, including cover and deep-rooting crops
(5) Tillage
(6) Organic farming
(7) Irrigation
(8) Biochar
(9) Lignocellulosic crops (e.g., agroforestry, bioenergy production) and
(10) Application of inorganic carbon.

We classified these practices according to their effect on SOC, availability and the technological requirements for the farmers. For each management practice, we identified gaps of knowledge and emphasized their potential trade-offs. Beyond the environmental dimensions, increasing soil organic carbon via agricultural management practices will also influence sociological, economic and ethical aspects of our society. In this review, we synthesize the most recent scientific literature on how carbon sequestration can be optimized in croplands. Overall, this review is structed the following: In Section 2 we briefly explained the scientific foundation of SOC dynamics. In Section 3 we concentrate on current and potential future agricultural management practices leading to a synopsis enquiring if soils an unlimited carbon sink (Section 4) and conclusions (Section 5).

2. Scientific Foundation

2.1. Carbon Saturation Concept

Before going into the details of agricultural management practices and their responses to carbon sequestration, note that the soil mineral size fraction is crucial for SOC stabilization [27], especially fine-grained minerals (<20 µm); this includes clay minerals and oxides/hydroxides that are responsible for stabilizing (long residence time) organic carbon in soils [28–30]. They protect organic carbon from leaching through organo-mineral interactions (physico-chemical interactions) or limit the accessibility of organic compounds to the soil microbial community or restrict the oxygen supply for decomposers (physical protection) [29,31]). The mineral fraction < 20 µm is known to determine the theoretical maximum of carbon stored. The assumption is therefore that soils have a finite capacity to store carbon ("carbon saturation capacity") [32]. In that concept, the organic carbon associated with the coarse-sized particles is neglected because organic matter associated with sand-sized fraction is lost rapidly [32]. Overall, the building up of SOC stocks features a progressive development with marginal increases in the SOC stock once saturation is approached. Consequently, SOC stock increases are not directly proportional to carbon inputs. Furthermore, adding fresh organic material can promote the mineralization of "old" SOC ("priming effect"). This means that soil is not an unlimited sink for carbon [22]. At the same time, the carbon sequestration potential of European cropland could be limited [13,33]. Only depleted soils can temporarily accumulate carbon up to their optimum C content [13]. The soil organic carbon content of the topsoil (0–20 cm) remained constant [33] or declined by 25% [34] when constant agricultural management practices, such as fixed crop rotation, were applied on fields over the last 20 years—this is the "business as usual" variant. As a consequence, achieving the "4-per-mille initiative" goal might be challenging.

2.2. Carbon Sequestration

The evaluation of soil management practices for sequestering atmospheric carbon in agricultural topsoils can be misleading because the terms carbon sequestration and carbon storage are often used interchangeably [25]. In order to avoid misunderstandings, we adopted the definitions of carbon sequestration as formulated in [35]: "*Process of transferring CO_2 from the atmosphere into the soil of a land unit through a unit plant, plant residues and other organic solids, which are stored or retained in the unit as part of the soil organic matter (humus). The sequestrated SOC process should increase the net SOC storage during and at the end of a study to above the previous pre-treatment baseline.*" The carbon sequestration potential of a certain management practice represents the maximum increase or decrease in SOC stock for a certain climate over a specific period of time and a certain soil depth, mainly 0–20 cm soil depth. Overall, a negative carbon sequestration potential represents a net loss of SOC, while a positive carbon sequestration corresponds to an increase of SOC stock. Except for recent management practices (e.g., biochar, agroforestry, bioenergy production, liming, and fertilization with silicate minerals), this review quantifies the carbon sequestration potential of agricultural management practices for 20 years [36].

2.3. Carbon Storage

The increase of carbon storage is defined as the increase of SOC stocks of a given land unit over a certain soil depth and period of time [36]. In the following, soil carbon storage is regulated by the organic carbon input and output, and changes in soil carbon storage do not necessarily account for the net removal of CO_2 from the atmosphere [22]. In other words, carbon storage is defined as a mass change for a certain soil depth over a certain time period, whereas the carbon sequestration is formulated as a rate for a certain soil depth over a certain time period.

3. Cropland Management Practices

3.1. Mineral Nitrogen Fertilization

Overall, the impact of nitrogen (N) fertilization on soil organic carbon (SOC) is characterized by two contrasting trends. On the one hand, N fertilization fuels primary production, thus enhancing the above- and belowground biomass, which in turn can enrich SOC stocks [37]. On the other hand, nitrogen fertilization can stimulate biodegradation of litter and soil organic matter [38]. This reduces SOC stocks [39]. Thus, an optimal nitrogen supply might be crucial for soil carbon sequestration [40]. In a global meta-analysis by [39], N fertilization reduced SOC in agricultural soils by 10%, whereas in another meta-analysis of 340 paired observations, N fertilization enhanced SOC storage by 3.5% [41]. From the dataset compiled by the authors of [41], N fertilization apparently mainly affected the plant organic matter pool, whereas the SOC pool was altered to a lesser degree. Furthermore, they attributed the stimulating effect of N fertilization on SOC storage to the higher growth of aboveground biomass and less to the root biomass. In contrast, the meta-analysis of [39] revealed that N fertilization fueled soil organic matter mineralization. The authors concluded that the earth system models should differentiate between organic carbon inputs from above- and belowground biomass because the impact of N fertilization on SOC storage was interrelated with (above- and belowground) biomass.

Soil organic matter can be stabilized physically through macro- and micro-aggregation or interactions with silt and clay particles [17] or/and be stabilized biochemically through the formation of recalcitrant SOM compounds [27,42]. Apparently, "old" SOM with a decadal or centennial turnover time was rich in nitrogen and soil protein [43]. The authors of [44] also assumed that protein-rich compounds are responsible for long-term soil organic matter stabilization/sorption. However, little experimental evidence is available for interactions between the nitrogen application rate and assimilation of recalcitrant organic carbon. In nitrogen-limited environments, the soil microbial community utilized nitrogen from stable SOM to meet its nutrient requirements for growth and reproduction [45,46]. Confirming the aforementioned, the authors of [47] determined that nitrogen fertilization improved the stable SOC pool (fine fraction < 0.4 mm) by enhancing litter decomposition and simultaneously reducing microbial nutrient mining. Nevertheless, the authors of [48] observed that mineral fertilization tended to increase the particulate organic matter in soils, while organic matter occluded in silt and clay sized fraction was decreased, yielding less stable forms of C.

The average **carbon sequestration potential** of mineral N fertilization in agricultural topsoils (0–10/30 cm) was—20 $\pm$ 210 kg C ha^{-1} y^{-1} [25,48–51] (Figure 1). Nevertheless, mineral fertilization decreased the SOC stock at a rate of -198 ± 29 kg C ha^{-1} y^{-1} and the unfertilized control revealed an even higher humus deficit of -457 kg C ha^{-1} y^{-1} [48]. Considering the greenhouse gas emissions during fertilizer production, the carbon sequestration potential of mineral fertilization remained neutral [52]. Especially in North America and Europe, mineral N fertilizer is already applied at a near optimum rate. This means a very low likelihood of further enhancing SOC stocks [50].

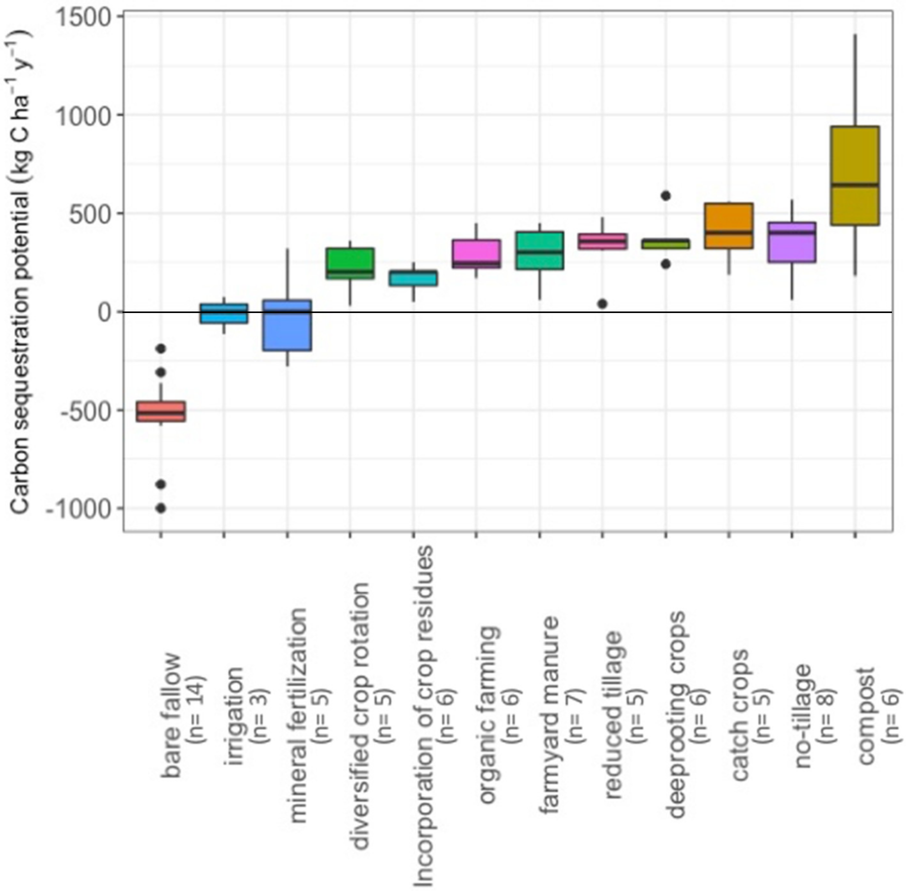

Figure 1. Carbon sequestration potential of agricultural management practices observed in the topsoil (0–20/30 cm) over at least 20 years, in ascending order. Negative C sequestration potential causes net SOC stock losses, while it is the opposite for C sequestration potential > 0. The respective references are given as Supplementary Materials. Each agricultural management practice is assigned a different color. Box- and whiskers diagrams show the median, 5th, 25th, 75th, and 95th percentiles for the carbon sequestration.

Similarly to solely mineral nitrogen fertilization, chemical nitrogen, phosphorus, and potassium fertilizers (NPK) increase crop yields [13,53], thus the elevated plant and root biomass increased soil microbial biomass as well as the SOC stock [22,54,55]. In contrast to no-fertilizer conditions, a meta- analysis of 84 long-term trails revealed that NPK, N, P, and K fertilization can enhance the SOC storage of the upper soil layer (0–20 cm) by 10, 5, 5, and 2%, respectively [55]. Furthermore, they found out that N and P fertilization increased the root biomass and root exudates, which in turn enhanced the SOC storage. Moreover, N/P ratio negatively corresponds to soil C storage. Long- term fertilization experiments with different soil types and cropping systems revealed that the impact of mineral NPK fertilizers on SOC sequestration rely on soil parameters, mainly the soil available N content and soil pH [56]. Besides enhanced primary production, P fertilizers can affect soil C sequestration by impacting arbuscular mycorrhizal fungi. In contrast to solely nitrogen fertilizers, the application of NPK reduces the colonization of arbuscular mycorrhizal fungi, thus reducing mycorrhiza-mediated nutrient plant uptake, which in turn negatively affects the soil C sequestration [57,58]. However, the role of arbuscular mycorrhizal fungi in the terrestrial carbon cycling is largely overlooked, especially its impact on the carbon sequestration potential [59].

Overall, the nutrient stoichiometry has shown to impact the microbial biomass C assimilation and re-assimilation of SOM (C:N:P:S 10,000:833:200:143) [60].

3.1.1. Knowledge Gaps

Overall, the soil microbial community plays a major role in controlling terrestrial carbon cycling [16]. The carbon use efficiency, which determines the fate of carbon during decomposition, is strongly linked to nitrogen and phosphorus (P) availability and may be further affected by the accessibility of potassium and micronutrients [61,62]. These connections need to be addressed by further research. Above all, life cycle assessments (LCA) would enable a coherent synopsis of mineral N fertilizers.

3.1.2. Trade-Offs

Fertilization with reactive N increases nitrous oxide (N_2O) emissions from soils. These N_2O losses associated with N fertilization can be reduced by using an appropriate fertilization rate (amount, timing), by enhancing the fertilizer use efficiency as well as by incorporating N-fixing crops in the crop rotation [63,64]. Importantly, the frequent overuse of mineral N fertilization can adversely affect adjacent water bodies and biodiversity (eutrophication) [65].

Overall, CO_2 emissions emitted by fertilizer production exceed the sequestered amount of soil carbon [51]. Globally, 2–3% of the anthropogenic CO_2 emissions are emitted during the production of mineral fertilizers [66], and the net greenhouse gas emissions for mineral fertilization amounted to 2000 kg CO_2-eq ha^{-1} y^{-1} [48].

Long-term mineral N fertilization increases nitrogen availability in soils, whereby changes in the nutritional status over a long time period can contribute to eutrophication [67].

3.2. Organic Amendments

Organic amendments affect the SOC pool in two ways: (I) Organic fertilization stimulates net primary production; thus, atmospheric carbon is fixed through photosynthesis [68–70]; (II) organic amendments are an additional source for the existing SOC pool [71]; (III) similarly to mineral fertilization, organic fertilization may stimulate SOC biodegradation [22]. Note, however, that using external carbon sources may not contribute to climate change mitigation [66,70,72]. Applying organic fertilizers mostly results in a displacement, with high organic carbon concentrations at specific sites but reduced concentrations at donating sites [72]. Overall, the alternative usage of organic material is crucial and net sequestration will occur (a) when organic fertilizers are produced for a particular cropland field or (b) when the carbon of the existing fertilizer would otherwise be lost, e.g., to the atmosphere by burning [70] or with food wastes.

3.2.1. Farmyard Manure

Organic fertilizer such as cattle/pig/poultry manure is rich in organic matter and can therefore enhance the soil organic carbon stock [11,24,25,49–51,73]. However, such organic amendments can increase soil pH, which in turn can enhance the solubility of soil organic matter [74]. Furthermore, farmyard manure appears to be rapidly degraded in soil; this enhanced microbial activity (priming effect) may reduce the SOC stock [75]. Beyond enhancing biodegradation, the application of farmyard manure is reported to improve soil structure and water holding capacity in agriculturally managed soils [51].

The average **carbon sequestration potential** of farmyard manure amounted to 292 $\pm$ 132 kg C ha^{-1} y^{-1} [11,24,25,49–51,73] (Figure 1). In temperate climates, solid manure application of 5 to 10 t ha^{-1} y^{-1} resulted in a carbon sequestration rate of 160 kg C ha^{-1} y^{-1} [11]. Overall, the impact of farmyard manure on the SOC stock varied among types. The authors of [76] reported that in Denmark, during the first 8 years after implementation, cattle slurry, pig slurry, and anaerobically digested slurry increased the SOC stock of the topsoil (0–25 cm) by 300 kg C ha^{-1} y^{-1}, 200 kg C ha^{-1} y^{-1} and 200 kg C ha^{-1} y^{-1}, respectively. A recent meta-analysis of 217 datasets showed that farmyard manure can enhance the carbon sequestration potential of agricultural topsoils (0–20/30 cm) by 409 kg C ha^{-1} y^{-1} [24]. In contrast to mineral fertilization, organic fertilization enhanced the carbon sequestration potential of Mediterranean soils by 23.5% [52]. An analysis of 80 long-term experimental sites in Europe showed that bovine farmyard manure increased SOC stocks by 33%, while liquid slurry increased the stocks by 17%, a value that was also achieved through mineral fertilizer application (16%) [77]. However, the impact of farmyard manure on SOC declined with time and, after a decade, no SOC enhancement was recorded [52]; in another case, a new equilibrium was reached after 50 years [78].

3.2.2. Compost Application

Compost consists mostly of plant-based material, e.g., biowaste or sewage-sludge, which is decomposed under aerobic conditions in a controlled environment [79]. The composition/quality of the final compost varies according to the source and duration of the maturation phase. Consequently, the quality of composts are inhomogeneous and they may even contain toxic substances such as heavy metals and organic contaminants [80]. In long-term field experiments, fertilization with compost enhanced SOC stocks [25,48,81]. In a comparative long-term study with four different compost types, the authors of [81] pointed out that compost application should follow a regular pattern if SOC storage is to be improved. Overall, the average **carbon sequestration potential** of compost application was 714 ± 404 kg C ha^{-1} y^{-1} [25,48–51,73] (Figure 1). Additionally, that value varied with the application rate: Rates of 8, 14 and 20 t ha^{-1} y^{-1} could potentially sequestered 115, 558 and 1021 kg C ha^{-1} y^{-1} [48].

3.2.3. Knowledge Gaps

Overall, the chemical analysis of manure and compost is often restricted to total C content, C/N ratio and pH [71], thus limiting the assessment and synthesis of field studies. Increasingly, methods evaluating the decomposition of organic fertilizers through short-term incubations or biochemical characterization [82,83] are being used to parameterize the quality of organic fertilizers. Those results can be further used to parameterize SOC models and may help in reassessing the impact of organic fertilizers on SOC pools (long-term/recalcitrant soil organic matter). Despite the advantages of these new approaches, studies evaluating the decomposition of organic fertilizers are rarely implemented [22]. Furthermore, an LCA would call for a precise analysis of the benefits and trade-offs of organic fertilizers.

3.2.4. Trade-Offs

Animal husbandry is a dominant source of greenhouse gases, and industrial animal husbandry annually emits 5.6–7.6 Gt CO_2-eq globally [84]. In the future, improved feed digestibility, grazing management, cultivation of legumes, and manure management (designed to reduce losses via volatilization and runoff) could potentially halve N_2O and CH_4 emissions from animal husbandry [84]. Additionally, CO_2 emitted during transportation could outrange the carbon sequestration potential of manure [70]. Thus, organic fertilizers are not always available on site, and emissions caused by transportation over 100 km can exceed the carbon sequestration potential by 30% [51]. Importantly, the process of composting also emits N_2O [51].

3.3. Crop Residues

Besides enhancing SOC stocks, the incorporation of crop residues into agricultural soils improves soil structure, reduces bulk density, reduces evaporation, decreases erosion and improves the infiltration rate in soils [23,85–87]. In agricultural management systems, where straw is used for thermal energy production or animal feeding/bedding, stubbles are cut short and the straw is removed. This reduces the overall amount of crop residues [88]. Generally, maize or perennial crops produce abundant residues, whereas root crops such as potatoes generate smaller amounts [11]. Residue C:N quality also influences SOC, and crop residues with a lower C:N ratio (e.g., soybean) promote microbial decomposition.

This would enhance the decomposition of soil organic matter [89]. Crop residues with a higher C:N ratio (maize) were typically associated with a SOC build up [89,90]. At similar crop residue management, SOC stocks increased with yields [91]. Nonetheless, due to the application of growth regulators and the selection of crop types with short stems, crop residues might not increase proportionally with crop yield. The authors of [92] did, however, report that crop residues with a low C:N ratio could increase the SOC stocks.

The predominant view in the scientific literature is that incorporating crop residues yields an average **carbon sequestration potential** of 168 ± 67 kg C ha^{-1} y^{-1} in the upper soil layer (0–20/30 cm) [25,49–52,73] (Figure 1). In a meta-analysis of 39 publications involving long-term field experiments, residue incorporation enhanced SOC stocks by 7% [86]. The authors of [93] reported that a decade after incorporation of straw, the carbon sequestration reaches a new equilibrium, i.e., a stable SOC stock in topsoil. In contrast, ref. [78] observed an increase in SOC stocks in only six out of 25 straw incorporation studies.

3.3.1. Knowledge Gaps

Since the incorporation of crop residues into soils is connected with tillage, this physical disruption of the soil surface might pose a risk for the SOC stock. Future analyses should consider such potential effects [94] and also more closely evaluate the impact of soil-borne diseases on crop health.

3.3.2. Trade-Offs

Incorporating crop residues can promote N mineralization, potentially enhancing N_2O and CH_4 emissions [23,70,86]. However, these greenhouse gas emissions can be reduced by implementing suitable tillage practices [95]. Moreover, conflicting goals—retention of crop residues for increasing SOC stock versus using residues for energy production—must be considered. In the future, the increasing economic viability of bioenergy use (due to rising oil prices etc.) may reduce the availability of crop residues [96].

3.4. Plant Cultivation

3.4.1. Crop Species

Terrestrial vegetation is a crucial element in the global carbon cycle because plants assimilate more than 10% of the atmospheric carbon emissions through photosynthesis [97]. Carbon assimilated by plants is either integrated into the biomass, released as root exudates, or respired back as CO_2 [98]. These translocational processes depend on the genetic variability among crop species and genotypes [99]. On average, crops assimilated 4.5 Mg C ha^{-1} y^{-1}, ranging from 1.7 Mg C ha^{-1} y^{-1} for barley (*Hordeum vulgare*) to 5.2 Mg C ha^{-1} y^{-1} for maize (*Zea mays*) [69]. These considerable differences reflect different internal C metabolisms [69]. In contrast to C3 crops such as barley, maize assimilates atmospheric C more efficiently through both the C4 photosynthetic pathway and a larger leaf area [100]. Overall, most (61%) of the assimilated carbon was transported to the shoots, 20% to roots and 7% were transferred to the soil [69]. Maize and ryegrass (*Lolium perenne*) had the greatest allocation to soil (1.0 Mg C ha^{-1} y^{-1} or 19% of the total assimilation), whereas wheat (*Triticum aestivum*) allocated 0.8 Mg C ha^{-1} y^{-1} (23% of the total assimilation) [69]. Overall, root growth and rhizodeposition were the main sources of SOC [101–103]. Globally, the belowground biomass could assimilate 24.7 ± 5.7 Pg C y^{-1}. Accordingly, the belowground net primary production makes up 46% of the global terrestrial net primary production [101]. On average, the dry root biomass was 177 ± 43 g m^{-2} and 101 ± 26 g m^{-2} for cereals (including barley and wheat) and cover crops, respectively [104]. However, these values were measured only in 30 cm soil depth. The subsoil carbon sequestration potential with deep-rooting crops is covered in section "Cultivation of deep-rooting crops" below.

3.4.2. Crop Rotation

The vegetal cover of agricultural soils and the manner of its management impacts SOC storage. The input of organic matter through plant biomass predominates in the topsoil and declines with soil depth [105]. In contrast to single cropping systems (monoculture with cereals or maize), diverse crop rotations with various main crops and/or perennial crops/forages and/or cover crops yielded distinctly higher SOC stocks [94,106]. In agricultural fields, crop diversity can be increased on a temporal (crop rotation, catch crops) and spatial scale (several plant species at the same time, cover crop mixture). Crop rotational diversity, the use of organic fertilizers/amendments and/or perennial cropping systems have the potential to accumulate more SOC than conventional (single) cropping systems [11,25]. Beyond its beneficial effects on SOC stocks, a diverse crop rotation can also increase soil microbial diversity, soil aggregate stability or even enhance organic carbon in the subsoil via deep-rooting crops [99,107,108]. Since roots have an up to 2.3 times higher retention of carbon than the aboveground biomass, deep-rooting crops are decisive for the SOC storage [101,102]. Again, this effect predominates in the topsoil and declines with soil depth [105]. The following sections discuss two suitable methods for sequestering carbon in a crop rotation—the cultivation of deep-rooting crops and planting catch crops—in further detail.

Overall, diversified crop rotational systems can enhance the **carbon sequestration potential** of agricultural topsoils (0–20/30 cm) by 216 $\pm$ 117 kg C ha^{-1} y^{-1} when compared with single cropping systems [25,94,109–111]. Compared to cereal-dominating cropping systems, incorporating legumes in the rotation in Sweden after 35 years enhanced the carbon sequestration potential by 360 and 590 kg C ha^{-1} y^{-1} in the topsoil (0–20 cm) at sites with clay and loam texture, respectively [112]. Moreover, in the loamy soils, changes of the SOC stock were detected along the whole soil profile (0–60 cm), whereas for the clay soils the subsoil SOC (>20 cm) remained unaffected [112]. The addition of soybean (*Glycine max* L.) into a corn monoculture increased the overall carbon sequestration potential of the topsoil by 200 $\pm$ 120 kg C ha^{-1} y^{-1}. In a global meta-analysis, incorporating catch crops increased the SOC stock of the agricultural topsoil (0–22 cm) by 350 $\pm$ 80 kg C ha^{-1} y^{-1} [94]. In Denmark, SOC stocks of the topsoil (0–25 cm) increased with green manure by 400 kg C ha^{-1} y^{-1} [76].

Cultivation of Deep-Rooting Crops

Deep-rooting crop species and varieties can transfer carbon into the subsurface through root exudates (e.g., sugars, amino acids, and other organic acids), where a high carbon sequestration potential exists [113], especially if organic substances are protected in organo-mineral aggregates [3]. Plant species with deep-rooting systems are alfalfa (*Medicago sativa*), sunflower (*Helianthus annuus*), or perennial crops such as grass, grass-clover, and legume- and alfalfa-grass mixtures [114,115]. For instance, in Sweden, the implementation of grass-clover into the crop rotation increased SOC contents by 8% in 20 years [116].

Overall, the cultivation of deep-rooting crops can sequester 374 $\pm$ 117 kg C ha^{-1} y^{-1} [50,109,112,117] (Figure 1). Considering the whole soil profile (0–90 cm), deep-rooting crops (alfalfa) enhanced the SOC stock at a rate of 380 kg C ha^{-1} y^{-1}, whereas in the topsoil (0–30 cm) that value was 240 kg C ha^{-1} y^{-1} [117]. A meta-analysis revealed that carbon sequestration via N-fixing crops is limited to the first 20 years; thereafter, N_2O emissions exceed the ability of such crops to mitigate CO_2 emissions [118].

Another advantage is that deep-rooting crops can use resources such as water and nutrients from the subsurface horizon. This helps prevent nutrients, especially N, from leaching, making plants more resilient to drought [90,119]. Finally, deep-rooting crops enhance deep infiltration and improve the soil pore connectivity [51]. The biopores created by such crops can enhance the expansion of the subsequent crops. However, plant breeding has focused on yield increases for decades [120]. Consequently, both optimized fertilization and genetic selection have resulted in crops with a high aboveground biomass and a limited root growth.

Catch Crops

Catch crops are sown after harvest of the main crop (such as cereals) or undersown in/with main crops. This creates a permanent vegetal cover of the arable land and an additional period of carbon assimilation [121]. Catch crops therefore prevent soil erosion, weeds and subsoil autumn losses of nitrate and other nutrients [94,122–124]. Different grass and legume varieties, rye or several cruciferous species are suitable catch crops [125–128]. They are used as fodder crops for ruminants or are sown as a soil improvement, so-called green manure. If catch crops remain on the field, the additional plant organic matter increases SOC stocks. Accordingly, implementing catch crops in crop rotations can yield a positive SOC balance.

On average, the **carbon sequestration potential** of an annual cultivation of catch crops amounted to 403 ± 142 kg C ha^{-1} y^{-1} in agricultural topsoils (0–25/30 cm) [76,94,129–131] (Figure 1). In Denmark, SOC stocks of the topsoil (0–25 cm) were increased by 210 kg C ha^{-1} y^{-1} after introducing catch crops into the rotation [76]. A meta-analysis of 131 studies across the globe reported a mean carbon sequestration rate of 560 kg C ha^{-1} y^{-1} [131]. Furthermore, cover cropping under permanent crops (vineyards or orchards) led to a carbon sequestration rate of 550 kg C ha^{-1} y^{-1} [129].

3.4.3. Knowledge Gaps

Crop species and genotypes with a distinct root system (high root biomass) can promote soil carbon storage of the subsoil as well as the nutrient and water acquisition in deep soil layers. Overall, other benefits and costs of deep-rooting crops remain largely unclear. Especially the conflicting goals of enhanced inputs via root biomass (rhizodeposition) versus the priming effects require further assessment [22].

Furthermore, secondary plant metabolites may affect soil organic matter degradation. For instance, ref. [132] showed that polyphenol-rich plant litter can inhibit bacterial mineralization of both carbon- and nitrogen-containing compounds as well as enhance nitrogen recycling by mycorrhizae and SOM. Nonetheless, studies evaluating the effect of secondary plant metabolites are rare and further research would be an asset.

Due to the mostly shallow sampling approach (0–30 cm soil depth), the effect of deep-rooting (cover) crops below the plough layer might be largely underestimated [112,116,133]. Additionally, long-term effects of deep-rooting crops on SOC stocks are important, but the extent is largely unknown due to short-term experiments (<10 years). Another aspect that might influence crop rotational decisions is soil-borne diseases. Such diseases are probably influenced by plant (root)-microbiome interactions. Extensive research on the root- associated microbial community could improve the resistance breeding against soil-borne pathogens [134]. Overall, future research should address crop rotations and the combinations of crops or genotypes with different rooting depths.

3.4.4. Trade-Offs

Catch crops are a source of soil greenhouse gas emissions (N_2O, CO_2) [125,135]. Despite their carbon sequestration potential, nitrogen-fixing catch crops can become a net source of greenhouse gas emissions, especially N_2O, over decades [118].

Despite its advantages, catch crop cultivation is not always possible. Temporally, it is hardly achievable prior to fall-seeded crops or after late-harvested crops such as potatoes, maize, and sugar beet. Water scarcity in autumn can also restrict the planting/growing of catch crops, whereas too low winter temperatures and sustained frost periods can prevent cover crops from being destroyed. This then entails weed control in the main crop due to cover crop reestablishment in the following spring. At the same time, new studies show that winter freezing cover crop species have a water consumption similar to that of bare soil and thus have no significant impact on the water balance [11]. Due to water scarcity, costs, and the lack of experience, the cultivation of catch crops (sown between main crops or sown underneath crops) is still restricted globally [70]. Importantly, the evaluation of 16 long-term experimental sites across Europe showed that bare soil impairs the SOC stock most strongly: Without any addition of organic matter (crop residues, organic fertilizers) the SOC decreases markedly after 10 years [13].

3.5. Tillage

Conventional tillage such as ploughing mechanically destroys soil aggregates on the soil surface, exposing formerly protected SOM to decomposition by microorganisms [136]. It also promotes soil erosion, reducing SOC stocks [137–139]. Fields cultivated with no- or reduced tillage practices proved to have higher SOC contents in the topsoil (0–10 cm) than under conventional tillage such as moldboard ploughing [52,140,141]. However, with increasing soil depth (>10 cm) no impact of tillage practices on SOC storage could be found [141]. The tillage-induced SOC losses were associated with soil erosion [140]. Moreover, minimizing mechanical disturbances enhances soil health by improving aggregate stability, thereby reducing erosion [142,143]. In Mediterranean climates, topsoil SOC (0–10 cm) was more abundant in fields managed with no-tillage than under moldboard ploughing (ploughing depth of 30/35 cm) [141]. However, with increasing depth (>10 cm) no impact of tillage practices on SOC storage was detected [141]. In a further study on Mediterranean soils, no-tillage practices proved to increase SOC stocks (5–40 cm) by 7% compared to minimum tillage practices [52].

Reduced/no-tillage practices have been controversially discussed as a climate mitigation option [73,144,145] due to their high uncertainties—even when adjusted for equivalent soil mass [146]. Overall, the effects of reduced and no-tillage practices on carbon sequestration are minimal [73,144,145] and relatively insignificant when the whole soil profile (0–60 cm) is considered [12,25,73,144,145,147]. Nevertheless, in the topsoil (0–20/30 cm) no-tillage practices had a **carbon sequestration potential** of 343 ± 167 kg C ha^{-1} y^{-1} [25,51,111,141,147,148], and reduced tillage practices can sequester 324 ± 138 kg C ha^{-1} y^{-1} in the upper soil layer (0–20/30 cm) [25,49,51] (Figure 1). However, note that the uncertainties regarding no-tillage practices as a climate mitigation tool are high. In a global meta-analysis, the 95% confidence interval for a sandy soil in warm climates ranged from -100 to 460 kg C ha^{-1} y^{-1} [146]. The carbon sequestration potential of Mediterranean topsoils (0–30 cm) ranged between -60 kg C ha^{-1} y^{-1} and 400 kg C ha^{-2} y^{-1} for conventionally tilled and no-tilled soils, respectively [141]. Furthermore, in a global database of 311 long-term experiments, converting conventional tillage to no-till practices enhanced the carbon sequestration potential by 460 ± 380 kg C ha^{-1} y^{-1} in the topsoil layer 0–15 cm [147]. Overall, the carbon sequestration potential increased rapidly during the first ten years (+0.75 Mg ha^{-1} y^{-1}), whereas after 15–20 years a new equilibrium was reached [111,141]. The authors of [149] reported that especially intensively tilled Chernozems are susceptible to SOM losses under climate change.

The direct mechanical effect on soil organic matter mineralization is questionable [22]. The authors of [150] suggested that only a part of the SOC stock differences are induced by the conversion from conventional tillage to no-tillage. The effects of no-tillage practices on SOC are more likely caused by the concomitantly altered carbon inputs, such as continuous vegetative cover and living roots, rather than by the reduced soil aggregate disruption after implementing no-tillage itself [150,151]. Several studies also related the absence of tillage to changes to certain crops. For example, the inclusion of temporary grassland with clover in the crop rotation is a typical practice when no-tillage practices are applied [151]. In contrast, for the transition of the grassland period to cereal production the soil is often tilled.

Despite its beneficial effects on SOC stocks and soil microbial activity, no-tillage practices are not very popular [152]. Conservation agriculture practices, such as no- or minimum tillage, cover cropping and diverse crop rotations, are applied on only 12.5% of the total global agricultural cropland [153].

3.5.1. Knowledge Gaps

Reduced/minimum tillage is not well defined but usually implies a reduction of tillage depth and/or frequency. Many studies do not differentiate between different types of tillage (e.g., chisel ploughing, moldboard ploughing, or disc harrowing) or do not account for tillage depth (e.g., conventional tillage and various forms of reduced tillage). This complicates assessing those factors, especially when tillage intensity varies from year to year [147]. Future studies would benefit from evaluating the impact of tillage on SOC stocks in different soil layers, especially including the subsoil [22,151]. Importantly, the calculation of SOC stocks based on fixed soil depths can overestimate the carbon sequestration potential of no-tillage practices. Using the equivalent soil mass approach is strongly recommended to overcome such problems [154].

Since reduced tillage practices can cause an accumulation of N, P, and K in the upper soil layer (0–20 cm) [155], the combination of reduced tillage and reduced fertilization should be examined in detail.

3.5.2. Trade-Offs

Contrary to conventional tillage, reduced tillage practices use more herbicides [156] but less fossil fuels [157]. An additional side effect of reduced tillage is that the soil may become more anaerobic; this promotes denitrification, which in turn may enhance the production of N_2O [78,158]. At the same time, no-tillage practices often result in lower crop yields than conventional tillage practices [88,158]. Tillage increases the mineralization rate of soil organic matter. As a consequence, CO_2 is released and SOC stocks are reduced [22].

3.6. Organic Farming

In organic farming systems, SOC stocks can be improved through (I) usage of organic fertilizers, (II) diversified crop rotation with legumes, as well as (III) cultivation of cover crops [159–161]. On average, organic farming practices **sequestered** 287 ± 102 kg C ha^{-1} y^{-1} [51,76,159,161–163] more carbon than conventional farming practices (Figure 1). In organic farming systems, organic fertilization with cattle manure and green manure (alfalfa) sequestered 160 kg C ha^{-1} y^{-1} and 180 kg C ha^{-1} y^{-1}, respectively [159]. A global meta-analysis of 68 datasets from 32 peer-reviewed publications showed that organic fertilization is the most important driver in increasing SOC stocks in organic farming systems [160]. Moreover, a conversion of all available cropland in the European Union into organic farming would sequester a total of 30 Mt carbon at once—equivalent to one quarter of the current agricultural emissions [163]. Allocating SOC increases to organic farming practices is challenging because all the aforementioned beneficial farming practices (particularly cover crops, legumes in the crop rotation and organic fertilizers) can be implemented in conventional farming as well. For instance, if organic fertilizers are applied on conventionally managed cropland at similar rates as in organic farming systems, then the SOC stocks were at similar levels in both farming systems [160].

On average, organic fertilizers, cover crops and diversified crop rotations are more frequently used in organic farming than under conventional management practices. In contrast, ploughing—a management practice prone to reduce the soil organic stock—is frequently used in organic farming systems to suppress weeds [161]. Beyond the carbon sequestration potential, organic farming enhances biodiversity and reduces the risk of eutrophication and water pollution [161]. Organic management practices are also characterized by low artificial external inputs (omission of chemically synthesized products such as pesticides, herbicides, or easily soluble mineral fertilizers). Such practices therefore consume less primary energy than conventional farming systems [164]. Compared with conventional farming practices, plant cultivation in organic farms produces lower emissions per hectare [165]. Since organic farming may result in lower yields [166], the emissions of organic farming per crop yield (product) are still under debate [165].

3.6.1. Knowledge Gaps

Towards a more sustainable development, future research in organic farming should include crop yields in the evaluation of greenhouse gas emissions. In animal production, LCA should be used to compare GHG emissions and increased SOC over the production chain.

The overall goal of the European Green Deal is to make the European Union the first climate-neutral continent by 2050. In order to achieve this ambitious aim, one of the targets is that 25% of the EU's agricultural land should be farmed in an organic manner [167]. Future research needs to address the impact of organic farming on SOC sequestration by further closing the current gaps of knowledge.

3.6.2. Trade-Offs

In mixed farming systems, CH_4 emissions are enhanced by ruminants through enteric fermentation. These emissions, however, could be compensated by increasing the SOC stocks in grasslands used for feeding the animals [161]. Due to the omission of herbicides, organic farming systems use tillage practices to control weeds. This, in turn, could negatively affect the carbon sequestration potential. Importantly, however, a full analysis of greenhouse gas balances (including fuel needed for management practices) showed that organic farming systems have a higher carbon sequestration potential than conventional farming practices [162]. In organic farming systems, organic fertilization, the incorporation of crop residues into agricultural soils and the cultivation of cover crops may increase N_2O emissions, but the cultivation of deep-rooting crops can reduce NO_3 leaching [90].

3.7. Irrigation/Water Table Management

Irrigation increases plant-available water in soils. This practice helps increase net primary production under dry conditions. The enhanced plant growth increases organic carbon inputs into agricultural soils, but the accelerated C and N mineralization might reduce the benefits of irrigation for SOC [168,169]. In a global meta-analysis the **carbon sequestration potential** of irrigation varied between 50 and 100 kg C ha^{-1} y^{-1} [170]. However, a field study revealed that irrigation reduced SOC stocks in 25–30 cm soil depth at a rate of -144 kg C ha^{-1} y^{-1} [49]. On average, the carbon sequestration potential of irrigation amounted to -13 ± 78 kg C ha^{-1} y^{-1} [49,51,170] (Figure 1).

3.7.1. Knowledge Gaps

Overall, the effects of irrigation and changes in the water table on SOC stocks and processing should be assessed further. Here, the newly invented subsoil soil irrigation system—a device installed at 25 cm soil depth—may provide special advantages (greater water use efficiency) over traditional irrigation systems [22].

3.7.2. Trade-Offs

Most of the negative impacts of irrigation could be mitigated (pumping cost) or avoided (leaching and runoff) when irrigation water management aimed at improving water use efficiency (or water productivity) are carried out. Deficit irrigation strategies of precise irrigation methods can sustain crop productivity while limiting the negative externalities, thus improving the capability of this AMP to help increasing SOC stock. Overall, water use efficiency, defined as the relationship between plant productivity (biomass or crop yield) and water use [171], is the evaluation criteria for sustainable irrigation. The impact of irrigation on SOC sequestration can be negligible or negative, because the carbon costs of pumping water can exceed the increased SOC stock benefits [51]. Beyond environmental side effects, consideration should be given to economic impacts such as costs for irrigation water and fuel to pump the water [51]. In regions with water scarcity, irrigation inevitably increases potential conflicts for water between agriculture, industry and household uses [172].

Furthermore, irrigation can boost denitrification and N_2O emissions from soils [173] and may exacerbate nitrate leaching as well as the runoff of agrochemicals (e.g., herbicides, pesticides, and insecticides).

3.8. Biochar

Biochar is the product of thermally processing organic materials (plant- or animal-based) at temperatures above 350 °C and under restricted oxygen supply ("pyrolysis") [174]. The porous, fine-grained and carbon-rich biochar is mostly recalcitrant [175]. The long residence time of biochar in soils is related to its condensed aromatic nature [176]. Considering its high recalcitrance, biochar offers a long-lasting sink for carbon in soils. Only a small proportion of biochar is labile, and its application to soil can induce "priming", in which microbial decomposition of soil organic matter is promoted over a short period of time [177]. Contradictory evidence concerning the "priming" effect is also available, with positive [178,179], neutral [180] and negative [181] effects on SOC stocks. Besides such short-term effects, biochar application reportedly improves SOC stocks in agricultural fields [182,183] through enhanced primary production [184], increased recalcitrant fractions of SOC [185,186] and enlarged SOC pools in the subsoil [187,188]. It may also enhance aggregate stability, increase soil water retention, reduce soil erosion and enhance the activity of soil biota [189–191]. Besides improved soil quality, biochar application proved to immobilize copper and cadmium in laboratory experiments [192].

Various articles estimate the average **carbon sequestration potential** of biochar application to be 1.6 ± 5.14 Mg C ha^{-1} y^{-1} [3,193–195]. Generally, the recalcitrance of biochar is the most decisive factor for evaluating its carbon sequestration potential, but stability assessments are still ongoing [196].

3.8.1. Knowledge Gaps

Overall, the assessment of recalcitrance has certain weaknesses. Besides the need to biochemically evaluate biochar recalcitrance, this calls for long-term strategic research that includes environmental and management factors [190]. Moreover, further research is needed to assess the sorption potential of biochar for organic pollutants (e.g., pesticides) or heavy metals/trace elements [197].

Beyond agronomic utilization, no EU legislation addresses biochar application on agricultural fields [187]. Until now, biochar application as a fertilizer on agricultural fields is regulated country-specifically. From an environmental point of view, LCA analyses of biochar fertilization would be beneficial.

3.8.2. Trade-Offs

On a large scale, biochar application is not feasible due to its production limits. Economically, the monetary costs of biochar exceed its economic advantages [193].

3.9. Lignocellulosic Crops

3.9.1. Agroforestry

Agroforestry combines woody perennials, such as trees and shrubs, with agricultural crop or grassland. Generally, agroforestry fulfils multiple functions simultaneously, including ecological (such as increased SOC stocks, improved soil fertility) and socioeconomic benefits (e.g., higher crop productivity and the provision of crops, fodder, or timber) [72,198,199]. Recent studies highlight a mean **carbon sequestration rate** of agroforestry systems of 725 ± 100 kg C ha^{-1} y^{-1} in (sub) tropical and temperate regions [72,198,200,201]. In order to fulfil the 4 per mille target on the global scale, agroforestry should be expanded to a proportion of 6 % of the agricultural land [202].

3.9.2. Bioenergy Production

Generally, bioenergy production intends to replace non-renewable fossil energy-based products by renewable plant-based products. Due to their high primary production, lignocellulosic crops, such as *Miscanthus*, poplar tree (*Populus* spp.) and switchgrass (*Panicum virgatum*), can capture large amounts of atmospheric CO_2 through photosynthesis in their above- and belowground biomass throughout the vegetation period [21,63,203]. After 6 years, the **carbon sequestration potential** of lignocellulosic crops ranged between 1050 and 710 kg C ha^{-1} y^{-1} (topsoil; 0–10 cm) for woody (popular and willow trees) and herbaceous species (switchgrass and *Miscanthus*), respectively [204].

3.9.3. Knowledge Gaps

Due to the lack of published data and field studies, the potential carbon sequestration of agroforestry and bioenergy production is still under debate.

3.9.4. Trade-Offs

The main challenges of **agroforestry** are the lack of long-term research studies, the lack of markets for timber, the higher work load and the limited awareness of advantages of agroforestry [70,198]. Due to the high investment costs and the high working time requirement, the success of agroforestry in Europe will mainly rely on the object funding provided by the EU through the European Agricultural Fund for Rural Development.

Overall, the cultivation of **crops for bioenergy** production further increases the demand for agricultural land [205]. Moreover, fertilization could increase anthropogenic N_2O emissions, thus reducing the climatic benefits of lignocellulosic crops [63]. Additionally, the authors of [206] observed that harvesting *Miscanthus giganteus* exported large amounts of potassium in autumn; potassium replacement by (mineral) fertilizers and the CO_2 emissions connected with fertilizer production should be considered.

3.10. Application of Inorganic Carbon

3.10.1. Carbonate Minerals (Liming)

Liming can improve SOC by enhancing primary production (improved nutrient availability) or ameliorating the soil structure (bridging effects of carbonates). In calcium carbonate-rich soils, free calcium can bind with organic matter and form complex aggregates; this physically protects organic matter from microbial decomposition. Liming, however, can also stimulate soil microbial activity when applied to bring pH into a range of plant optimum, thus reducing SOC stocks [207].

Since liming is often combined with other fertilizers, its effect on SOC is challenging to estimate [207]. Various studies have found that liming either increased [208], decreased [209] or had no effect [207] on SOC stocks. In Brazil, liming (dolomitic lime) enhanced the SOC stock in the topsoil (0–20 cm) of a dystrophic red latosol (Oxisol), with an mean **carbon sequestration** rate of 300 kg C ha^{-1} y^{-1} over 15 years [208]. Nonetheless, published data on how liming affects SOC stocks remain scarce, and a global meta-analysis yielded no clear assertion [207].

3.10.2. Silicate Minerals

Carbon can be fixed permanently as pedogenic carbonates through chemical weathering of silicate minerals [210]:

$$CaSiO_3 + 2\,CO_2 + H_2O \text{ -> } Ca^{2+} + 2\,HCO_3{}^- + SiO_2$$

In an experimental field trial in a New Hampshire forest, applying 3.5 t/ha calcium silicate minerals (wollastonite) doubled the net removal rate of bicarbonate in the runoff of the catchment [211]. Thus, silicate minerals (wollastonite) proved to be an sink for carbon, and a global application could potentially sequester roughly 2% of global fossil fuel emissions [66].

3.10.3. Knowledge Gaps

Overall, the extraction of inorganic carbon is often associated with environmental problems. This calls for rigorous LCAs. The lack of published data and field studies makes assessments of its carbon sequestration potential inconclusive. Finally, little is known about how the application of inorganic carbon affects SOC processing/stabilization or soil aggregation and structure.

3.10.4. Trade-Offs

The production, transportation and application of inorganic carbon requires energy. This entails CO_2 emissions. Note also hat if demand for inorganic carbon increases, the enhanced production rates may adversely affect the environment or human health (e.g., dust inhalation) at extraction sites [70].

On one hand, **liming** can reduce the availability of essential nutrients (e.g., phosphorous, zinc, and manganese), while on the other hand it can lessen the availability of potential toxic elements such as cadmium [212]. Nevertheless, by stimulating the soil microbial community, liming is associated with CO_2 emissions [70].

After applying **silicate minerals**, the increased HCO_3^- in runoff waters may enhance ocean alkalinity and promote the growth of calcareous organisms [210]. From a financial perspective, the high investment costs of silicate minerals make its application uneconomical [66].

4. Synopsis—Are Soils an Unlimited Carbon Sink?

Agricultural management practices can sequester organic carbon in agricultural topsoil by enhancing primary production (with e.g., mineral and organic fertilization, irrigation), by applying additional organic carbon (manure, compost, incorporation of crop residues, biochar or cover crops), enriching subsoil organic carbon (deep-rooting crops), improving aggregate stability (no-tillage), replacing non-renewable fossil fuels (bioenergy production) or integrating woody biomass (agroforestry). All these processes allow a net removal of CO_2 from the atmosphere. Beyond the role of agricultural management practices, further constraints directly or indirectly affect the carbon sequestration potential of cropland soils. These constraints are summarized in the following section.

4.1. Bare Fallow—A Threat for SOC Stocks?

As opposed to sustainable agricultural management practices, such as conservation agriculture, the soil in conventional cropping systems is often left bare after harvest. Accordingly, such fields produce no noticeable amount of biomass over much of the year [213]. Except for the atmospheric deposition or weeds, the carbon inputs in periods of bare fallow are close to zero [214]. Above all, regaining the carbon losses from bare fallow periods is mostly not achievable, and agricultural management systems with bare fallows are mostly associated with a net loss of carbon [50,214–216].

Under current agricultural management practices, Swiss agricultural topsoils (0–20 cm) are losing SOC at a rate of 290 kg C ha^{-1} y^{-1} [215]. Among such practices, bare fallow resulted in the overall highest SOC losses at a rate of -531 ± 198 kg C ha^{-1} y^{-1} in the topsoil (0–20 cm) over 20/50/100 years relative to the start of the experiment [49,50,148,214,216,217] (Figure 1). Carbon is mostly depleted from the topsoil, whereas in subsoil (25–100 cm) it declined at a rate of -145 ± 5 kg C ha^{-1} y^{-1} [216].

4.2. Climate Change

In the absence of profound knowledge on how SOC cycling responds to a changing global climate, the estimates for the future SOC sequestration potential involve a considerable element of uncertainty [218]. According to [218], the following aspects must be addressed further: (I) Temperature sensitivity of soil organic matter [219,220], (II) equilibrium between organic carbon input and output under accelerated soil decomposition and enhanced primary production [136], and (III) interactions of global warming and changes in land use [221,222] and atmospheric composition [66,223] (e.g., rising CO_2 levels). In a current earth system model (Community Earth System Model—CESM, validated with LMER model selection), temperature rise accelerates SOC losses, and under a temperature rise of 1 degree, 30 ± 30 Pg carbon could be potentially lost within a year [224]. This positive carbon-climate feedback could potentially quicken climate change [224]. Furthermore, future climate conditions can initiate a sustained trend reversal, and ARMOSA model for future climate scenarios (Representative Concentration Pathway (RCP) 6.0) forecasted SOC depletion rates ranging from 160 to 88 kg ha^{-1} y^{-1} [148]. Moreover, under conditions of climate change the frequency and intensity of droughts and storm events are expected to increase in the near future. This is crucial since high intensity rainfall on dry soils have shown to multiply organic carbon exports from agricultural land to streams many times over [225].

Moreover, anthropogenic climate change and desertification of agricultural land will reduce the available land to sequester atmospheric carbon and to produce food. Prolonged droughts and high air temperatures may also be challenging for animal husbandry, especially in water-scarce regions. This will make dietary changes towards more plant-based diets more important in the near future.

4.3. Soil Sealing

Globally, land consumption threatens soils and their functions [226]. Due to the massive removal of topsoil and minimal accumulation of belowground C underneath sealed surfaces via root growth, urban soil sealing restricts soil C storage and is associated with substantial losses in C storage [227]. Urban sprawl/expansions are consuming agricultural land. In Europe, about 9% of the surface area is sealed, and artificial surfaces are increasing at an annual rate of 0.75% [228]. In the period 2012–2018, the annual land take in the European Union consumed 440 km^2 of agricultural land [8]. The loss of cropland with a high theoretical production potential is generating particular pressure on soils, ecosystem services and on future food security [229]. In 2006, the European Commission considered surface sealing as one of the major soil threats [229]. Despite being a pressing threat, no EU legislation currently protects soils from urban sprawl [230,231]. In Germany, for instance, a federal guideline is in place to deal with soil protection, whereas in Austria, soil protection is regulated by the regional authorities. In the future, the European Commission plans to harmonize those national legislations and regulations with the Soil Thematic Strategy [8]. As part of the European Green Deal, the update of this Soil Thematic Strategy aims to achieve land degradation neutrality by 2030, and by 2050 no net land take should occur in the EU [8].

4.4. Consumer Behaviour

The current global food sector emits 14 ± 3.4 Gt CO_2eq y^{-1} [232]. Global trade may shift environmental pressures to other countries; thus, agricultural food production should increasingly meet local consumer demand. In Austria, for example, the agricultural self-sufficiency regarding vegetables, fruits, wheat, dairy products and beef lies at 54, 59, 87, 128, and 141%, respectively [233]. Goods over 100% have to be exported, whereas products below 100% have to be imported. Due to an exponentially growing world population and an increasing per capita incomes, the pressure on food production is expected to increase by 50–90% in 2050 [234]. In a comparative analysis of food production systems, the highest greenhouse gas emissions are caused by a high demand for meat, whereas plant-based diets (vegan) produce the lowest emissions [235]. Therefore, a synergistic combination of dietary changes towards more plant-based diets, improved technologies and management, and reduced food loss and waste would help reduce the negative impact on ecosystems [234]. A reasonable option to counteract overproduction and food waste as well as to recycle organic carbon would be to compost food waste and/or organic wastes and apply them on agricultural fields. Food waste could also be digested in biogas plants and the digestates then used as an organic fertilizer.

4.5. Socio-Economic Limitations and Practical Considerations of Farmers

Given the low trading price of carbon and the high contribution margin of carbon- rich materials, farmers are unlikely to implement agricultural management practices to achieve the "4p1000" goal [26,66]. According to [26], the main motivation for farmers to change agricultural management practices is clear benefits, yield increases and long-term economic profitability. Accordingly, information exchange, financial incentives and the provision of appropriate infrastructure could encourage farmers to convert towards sustainable farming practices [236–238]. For instance, biochar technology is largely unknown to farmers, and the high transportation costs and high demand for organic residues make the application of biochar uneconomical for farmers [193]. The trading of CO_2 certificates by various providers is a questionable practice that should be carefully assessed in terms of benefits for farmers [11]. Finally, novel management practices often pose financial risks for farmers due to the high investment costs. In the future, object funding/subsidies (agroforestry) and/or securing the placing of customer products appear to be essential for the economic viability of sustainable farming practices [72,237,239].

5. Conclusions

Through two strategies—**increasing carbon inputs** and **reducing soil organic carbon losses**—agricultural management practices can improve carbon sequestration in soils. By enhancing primary production (fertilization, liming) and/or integrating additional organic carbon to soils (*additional biomass*: Catch crops, agroforestry, deep rooting crops; *external carbon sources*: e.g., compost, recalcitrant biochar), carbon can be added to agricultural cropland. Farmers can reduce the organic carbon losses from soils by minimizing the deliberate removal of crops (retention of crop residues), by reducing soil erosion (cover crops, reduced tillage) or by managing CO_2 from mineralization (reduced/no-tillage). Despite their advantages, the application of organic fertilizers (compost, farmyard manure) or biochar is limited by their local availability, and transportation causes additional CO_2 emissions. Importantly, CO_2 produced during manufacturing (e.g., mineral fertilizer) or pumping (e.g., irrigation) can outrange their beneficial value for carbon sequestration or the extraction of minerals and can cause severe environmental problems at the extraction sites (e.g., inorganic carbon, liming). Some practices can reduce nutrient availability (liming), change soil pH (biochar), promote nitrate leaching (irrigation) or cause problems in weed regulation (e.g., reduced/no-tillage). Greenhouse gas emissions are also associated with animal husbandry (CH_4, N_2O) or linked to soil processes such as improved mineralization of soil organic matter (CO_2) or denitrification (N_2O). Moreover, the carbon sequestration potential of relatively new management practices, such as the application of inorganic carbon or biochar and agroforestry, is not conclusive because published data on long-term field experiments are lacking. Based on the literature, bare fallows are responsible for the greatest SOC losses through SOM decomposition. Farmers are being requested to apply as many beneficial SOC-preserving practices as possible, but the overall benefit for SOC sequestration remains to be verified by an LCA under the respective soil and climate conditions. Summa summarum, the preservation of SOC is crucial because SOC is essential for soil fertility, soil health and ecosystem services, including primary production and climate regulation.

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References

1. Davidson, E.A.; Janssens, I.A. Temperature Sensitivity of Soil Carbon Decomposition and Feedbacks to Climate Change. *Nature* **2006**, *440*, 165–173. [CrossRef]
2. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* **2004**, *304*, 1623–1627. [CrossRef]
3. Paustian, K.; Lehmann, J.; Ogle, S.; Reay, D.; Robertson, G.P.; Smith, P. Climate-Smart Soils. *Nature* **2016**, *532*, 49–57. [CrossRef]
4. Singh, M.; Sarkar, B.; Sarkar, S.; Churchman, J.; Bolan, N.; Mandal, S.; Menon, M.; Purakayastha, T.J.; Beerling, D.J. Stabilization of Soil Organic Carbon as Influenced by Clay Mineralogy. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2018; Volume 148, pp. 33–84. ISBN 978-0-12-815179-2.
5. Janzen, H.H. Carbon Cycling in Earth Systems—A Soil Science Perspective. *Agric. Ecosyst. Environ.* **2004**, *104*, 399–417. [CrossRef]
6. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil Quality–A Critical Review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [CrossRef]
7. *COM(2006) 231; Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions-Thematic Strategy for Soil Protection*; European Commission: Brussels, Belgium. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF (accessed on 1 October 2020).
8. European Comission New Soil Strategy-Healthy Soil for a Healthy Life. Available online: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12634-Healthy-soils-new-EU-soil-strategy (accessed on 1 October 2020).
9. Van de Broek, M.; Baert, L.; Temmerman, S.; Govers, G. Soil Organic Carbon Stocks in a Tidal Marsh Landscape Are Dominated by Human Marsh Embankment and Subsequent Marsh Progradation. *Eur. J. Soil Sci.* **2019**, *70*, 338–349. [CrossRef]
10. Rumpel, C.; Amiraslani, F.; Koutika, L.-S.; Smith, P.; Whitehead, D.; Wollenberg, E. Put More Carbon in Soils to Meet Paris Climate Pledges. *Nature* **2018**, *564*, 32–34. [CrossRef] [PubMed]
11. Don, A.; Flessa, H.; Marx, K. *Die 4-Promille-Initiative "Böden Für Ernährungssicherung Und Klima"—Wissenschaftliche Bewertung Und Diskussion Möglicher Beiträge in Deutschland*; Johann Heinrich von Thünen-Institut: Braunschweig, Germany, 2018.
12. Spiegel, H. *Impacts of Arable Management on Soil Organic Carbon and Nutritionally Relevant Elements in the Soil-Plant System*; Habiliation; University of Natural Resources and Life Sciences (BOKU): Vienna, Austria, 2012.
13. Körschens, M.; Albert, E.; Armbruster, M.; Barkusky, D.; Baumecker, M.; Behle-Schalk, L.; Bischoff, R.; Čergan, Z.; Ellmer, F.; Herbst, F.; et al. Effect of Mineral and Organic Fertilization on Crop Yield, Nitrogen Uptake, Carbon and Nitrogen Balances, as Well as Soil Organic Carbon Content and Dynamics: Results from 20 European Long-Term Field Experiments of the Twenty-First Century. *Arch. Agron. Soil Sci.* **2013**, *59*, 1017–1040. [CrossRef]
14. Bradford, M.A.; Carey, C.J.; Atwood, L.; Bossio, D.; Fenichel, E.P.; Gennet, S.; Fargione, J.; Fisher, J.R.B.; Fuller, E.; Kane, D.A.; et al. Soil Carbon Science for Policy and Practice. *Nat. Sustain.* **2019**, *2*, 1070–1072. [CrossRef]
15. Lehmann, J.; Hansel, C.M.; Kaiser, C.; Kleber, M.; Maher, K.; Manzoni, S.; Nunan, N.; Reichstein, M.; Schimel, J.P.; Torn, M.S.; et al. Persistence of Soil Organic Carbon Caused by Functional Complexity. *Nat. Geosci.* **2020**, *13*, 529–534. [CrossRef]
16. Liang, C.; Schimel, J.P.; Jastrow, J.D. The Importance of Anabolism in Microbial Control over Soil Carbon Storage. *Nat. Microbiol.* **2017**, *2*. [CrossRef]
17. Schmidt, M.W.I.; Torn, M.S.; Abiven, S.; Dittmar, T.; Guggenberger, G.; Janssens, I.A.; Kleber, M.; Kögel-Knabner, I.; Lehmann, J.; Manning, D.A.C.; et al. Persistence of Soil Organic Matter as an Ecosystem Property. *Nature* **2011**, *478*, 49–56. [CrossRef]
18. Poeplau, C.; Don, A.; Six, J.; Kaiser, M.; Benbi, D.; Chenu, C.; Cotrufo, M.F.; Derrien, D.; Gioacchini, P.; Grand, S.; et al. Isolating Organic Carbon Fractions with Varying Turnover Rates in Temperate Agricultural Soils—A Comprehensive Method Comparison. *Soil Biol. Biochem.* **2018**, *125*, 10–26. [CrossRef]
19. Poeplau, C.; Don, A. Sensitivity of Soil Organic Carbon Stocks and Fractions to Different Land-Use Changes across Europe. *Geoderma* **2013**, *192*, 189–201. [CrossRef]
20. Vos, C.; Jaconi, A.; Jacobs, A.; Don, A. Hot Regions of Labile and Stable Soil Organic Carbon in Germany–Spatial Variability and Driving Factors. *SOIL* **2018**, *4*, 153–167. [CrossRef]
21. Ontl, T.A.; Cambardella, C.A.; Schulte, L.A.; Kolka, R.K. Factors Influencing Soil Aggregation and Particulate Organic Matter Responses to Bioenergy Crops across a Topographic Gradient. *Geoderma* **2015**, *255–256*, 1–11. [CrossRef]
22. Chenu, C.; Angers, D.A.; Barré, P.; Derrien, D.; Arrouays, D.; Balesdent, J. Increasing Organic Stocks in Agricultural Soils: Knowledge Gaps and Potential Innovations. *Soil Tillage Res.* **2019**, *188*, 41–52. [CrossRef]
23. Spiegel, H.; Mosleitner, T.; Sandén, T.; Zaller, J.G. Effects of Two Decades of Organic and Mineral Fertilization of Arable Crops on Earthworms and Standardized Litter Decomposition. *Die Bodenkult. J. Land Manag. Food Environ.* **2018**, *69*, 17–28. [CrossRef]
24. Bolinder, M.A.; Crotty, F.; Elsen, A.; Frac, M.; Kismányoky, T.; Lipiec, J.; Tits, M.; Tóth, Z.; Kätterer, T. The Effect of Crop Residues, Cover Crops, Manures and Nitrogen Fertilization on Soil Organic Carbon Changes in Agroecosystems: A Synthesis of Reviews. *Mitig. Adapt. Strateg. Glob. Chang.* **2020**. [CrossRef]

25. Minasny, B.; Malone, B.P.; McBratney, A.B.; Angers, D.A.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen, Z.-S.; Cheng, K.; Das, B.S.; et al. Soil Carbon 4 per Mille. *Geoderma* **2017**, *292*, 59–86. [CrossRef]
26. Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.-S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; et al. The 4p1000 Initiative: Opportunities, Limitations and Challenges for Implementing Soil Organic Carbon Sequestration as a Sustainable Development Strategy. *Ambio* **2020**, *49*, 350–360. [CrossRef]
27. Lehmann, J.; Kleber, M. The Contentious Nature of Soil Organic Matter. *Nature* **2015**, *528*, 60–68. [CrossRef]
28. Hassink, J. The Capacity of Soils to Preserve Organic C and N by Their Association with Clay and Silt Particles. *Plant Soil* **1997**, *191*, 77–87. [CrossRef]
29. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization Mechanisms of Soil Organic Matter: Implications for C-Saturation of Soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
30. Stewart, C.E.; Plante, A.F.; Paustian, K.; Conant, R.T.; Six, J. Soil Carbon Saturation: Linking Concept and Measurable Carbon Pools. *Soil Sci. Soc. Am. J.* **2008**, *72*, 379–392. [CrossRef]
31. Beare, M.H.; McNeill, S.J.; Curtin, D.; Parfitt, R.L.; Jones, H.S.; Dodd, M.B.; Sharp, J. Estimating the Organic Carbon Stabilisation Capacity and Saturation Deficit of Soils: A New Zealand Case Study. *Biogeochemistry* **2014**, *120*, 71–87. [CrossRef]
32. Barré, P.; Angers, D.A.; Basile-Doelsch, I.; Bispo, A.; Cécillon, L.; Chenu, C.; Chevallier, T.; Derrien, D.; Eglin, T.K.; Pellerin, S. *Ideas and Perspectives: Can We Use the Soil Carbon Saturation Deficit to Quantitatively Assess the Soil Carbon Storage Potential, or Should We Explore Other Strategies?* Biogeosciences Discussions, European Geosciences Union: Munich, Germany, 2017.
33. Gubler, A.; Wächter, D.; Schwab, P.; Müller, M.; Keller, A. Twenty-Five Years of Observations of Soil Organic Carbon in Swiss Croplands Showing Stability Overall but with Some Divergent Trends. *Environ. Monit. Assess.* **2019**, *191*. [CrossRef] [PubMed]
34. Stumpf, F.; Keller, A.; Schmidt, K.; Mayr, A.; Gubler, A.; Schaepman, M. Spatio-Temporal Land Use Dynamics and Soil Organic Carbon in Swiss Agroecosystems. *Agric. Ecosyst. Environ.* **2018**, *258*, 129–142. [CrossRef]
35. Olson, K.R.; Al-Kaisi, M.M.; Lal, R.; Lowery, B. Experimental Consideration, Treatments, and Methods in Determining Soil Organic Carbon Sequestration Rates. *Soil Sci. Soc. Am. J.* **2014**, *78*, 348–360. [CrossRef]
36. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Kanagawa, Japan; IPCC: Geneva, Switzerland, 2006; ISBN 978-4-88788-032-0.
37. Chaudhary, S.; Dheri, G.S.; Brar, B.S. Long-Term Effects of NPK Fertilizers and Organic Manures on Carbon Stabilization and Management Index under Rice-Wheat Cropping System. *Soil Tillage Res.* **2017**, *166*, 59–66. [CrossRef]
38. Recous, S.; Robin, D.; Darwis, D.; Mary, B. Soil Inorganic N Availability: Effect on Maize Residue Decomposition. *Soil Biol. Biochem.* **1995**, *27*, 1529–1538. [CrossRef]
39. Ladha, J.K.; Reddy, C.K.; Padre, A.T.; van Kessel, C. Role of Nitrogen Fertilization in Sustaining Organic Matter in Cultivated Soils. *J. Environ. Qual.* **2011**, *40*, 1756–1766. [CrossRef] [PubMed]
40. van Groenigen, J.W.; van Kessel, C.; Hungate, B.A.; Oenema, O.; Powlson, D.S.; van Groenigen, K.J. Sequestering Soil Organic Carbon: A Nitrogen Dilemma. *Environ. Sci. Technol.* **2017**, *51*, 4738–4739. [CrossRef]
41. Lu, M.; Zhou, X.; Luo, Y.; Yang, Y.; Fang, C.; Chen, J.; Li, B. Minor Stimulation of Soil Carbon Storage by Nitrogen Addition: A Meta-Analysis. *Agric. Ecosyst. Environ.* **2011**, *140*, 234–244. [CrossRef]
42. Gmach, M.R.; Cherubin, M.R.; Kaiser, K.; Cerri, C.E.P. Processes That Influence Dissolved Organic Matter in the Soil: A Review. *Sci. Agric.* **2020**, *77*. [CrossRef]
43. Bol, R.; Poirier, N.; Balesdent, J.; Gleixner, G. Molecular Turnover Time of Soil Organic Matter in Particle-Size Fractions of an Arable Soil. *Rapid Commun. Mass Spectrom.* **2009**, *23*, 2551–2558. [CrossRef]
44. Kleber, M.; Sollins, P.; Sutton, R. A Conceptual Model of Organo-Mineral Interactions in Soils: Self-Assembly of Organic Molecular Fragments into Zonal Structures on Mineral Surfaces. *Biogeochemistry* **2007**, *85*, 9–24. [CrossRef]
45. Chen, R.; Senbayram, M.; Blagodatsky, S.; Myachina, O.; Dittert, K.; Lin, X.; Blagodatskaya, E.; Kuzyakov, Y. Soil C and N Availability Determine the Priming Effect: Microbial N Mining and Stoichiometric Decomposition Theories. *Glob. Chang. Biol.* **2014**, *20*, 2356–2367. [CrossRef] [PubMed]
46. Derrien, D.; Plain, C.; Courty, P.-E.; Gelhaye, L.; Moerdijk-Poortvliet, T.C.W.; Thomas, F.; Versini, A.; Zeller, B.; Koutika, L.-S.; Boschker, H.T.S.; et al. Does the Addition of Labile Substrate Destabilise Old Soil Organic Matter? *Soil Biol. Biochem.* **2014**, *76*, 149–160. [CrossRef]
47. Kirkby, C.A.; Richardson, A.E.; Wade, L.J.; Passioura, J.B.; Batten, G.D.; Blanchard, C.; Kirkegaard, J.A. Nutrient Availability Limits Carbon Sequestration in Arable Soils. *Soil Biol. Biochem.* **2014**, *68*, 402–409. [CrossRef]
48. Erhart, E.; Tomasetti, A.; Pantic, S.; Haas, D.; Fuchs, K.; Bonell, M.; Hartl, W. Carbon Storage in Soil Size-Density Fractions after 20 Years of Compost Fertilization. *Acta Fytotechnica Zootechnica* **2015**, *18*, 110–112. [CrossRef]
49. Baumgarten, A.; Geitner, C.; Haslmayr, H.-P.; Zechmeister-Boltenstern, S. Der Einfluss Des Klimawandels Auf Die Pedosphäre. In *Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14)*; Verlag der Österreichischen Akademie der Wissenschaften: Vienna, Austria, 2014; ISBN 978-3-7001-7723-4.
50. Poulton, P.; Johnston, J.; Macdonald, A.; White, R.; Powlson, D. Major Limitations to Achieving "4 per 1000" Increases in Soil Organic Carbon Stock in Temperate Regions: Evidence from Long-Term Experiments at Rothamsted Research, United Kingdom. *Glob. Chang. Biol.* **2018**, *24*, 2563–2584. [CrossRef]
51. Freibauer, A.; Rounsevell, M.D.A.; Smith, P.; Verhagen, J. Carbon Sequestration in the Agricultural Soils of Europe. *Geoderma* **2004**, *122*, 1–23. [CrossRef]

52. Francaviglia, R.; Di Bene, C.; Farina, R.; Salvati, L.; Vicente-Vicente, J.L. Assessing "4 per 1000" Soil Organic Carbon Storage Rates under Mediterranean Climate: A Comprehensive Data Analysis. *Mitig. Adapt. Strateg. Glob. Chang.* **2019**, *24*, 795–818. [CrossRef]
53. Yang, J.; Gao, W.; Ren, S. Long-Term Effects of Combined Application of Chemical Nitrogen with Organic Materials on Crop Yields, Soil Organic Carbon and Total Nitrogen in Fluvo-Aquic Soil. *Soil Tillage Res.* **2015**, *151*, 67–74. [CrossRef]
54. Guo, Z.; Zhang, Z.; Zhou, H.; Wang, D.; Peng, X. The Effect of 34-Year Continuous Fertilization on the SOC Physical Fractions and Its Chemical Composition in a Vertisol. *Sci. Rep.* **2019**, *9*, 2505. [CrossRef] [PubMed]
55. Zhao, H.; Sun, B.; Lu, F.; Wang, X.; Zhuang, T.; Zhang, G.; Ouyang, Z. Roles of Nitrogen, Phosphorus, and Potassium Fertilizers in Carbon Sequestration in a Chinese Agricultural Ecosystem. *Clim. Chang.* **2017**, *142*, 587–596. [CrossRef]
56. Liang, F.; Li, J.; Yang, X.; Huang, S.; Cai, Z.; Gao, H.; Ma, J.; Cui, X.; Xu, M. Three-Decade Long Fertilization-Induced Soil Organic Carbon Sequestration Depends on Edaphic Characteristics in Six Typical Croplands. *Sci. Rep.* **2016**, *6*, 30350. [CrossRef]
57. Joner, E.J. The Effect of Long-Term Fertilization with Organic or Inorganic Fertilizers on Mycorrhiza-Mediated Phosphorus Uptake in Subterranean Clover. *Biol. Fertil. Soils* **2000**, *32*, 435–440. [CrossRef]
58. Liu, J.; Zhang, J.; Li, D.; Xu, C.; Xiang, X. Differential Responses of Arbuscular Mycorrhizal Fungal Communities to Mineral and Organic Fertilization. *Microbiol. Open* **2020**, *9*. [CrossRef]
59. Parihar, M.; Rakshit, A.; Meena, V.S.; Gupta, V.K.; Rana, K.; Choudhary, M.; Tiwari, G.; Mishra, P.K.; Pattanayak, A.; Bisht, J.K.; et al. The Potential of Arbuscular Mycorrhizal Fungi in C Cycling: A Review. *Arch. Microbiol.* **2020**, *202*, 1581–1596. [CrossRef] [PubMed]
60. Coonan, E.C.; Kirkby, C.A.; Kirkegaard, J.A.; Amidy, M.R.; Strong, C.L.; Richardson, A.E. Microorganisms and Nutrient Stoichiometry as Mediators of Soil Organic Matter Dynamics. *Nutr. Cycl. Agroecosyst* **2020**, *117*, 273–298. [CrossRef]
61. Crowther, T.W.; Riggs, C.; Lind, E.M.; Borer, E.T.; Seabloom, E.W.; Hobbie, S.E.; Wubs, J.; Adler, P.B.; Firn, J.; Gherardi, L.; et al. Sensitivity of Global Soil Carbon Stocks to Combined Nutrient Enrichment. *Ecol. Lett.* **2019**, *22*, 936–945. [CrossRef] [PubMed]
62. Poeplau, C.; Bolinder, M.A.; Kirchmann, H.; Kätterer, T. Phosphorus Fertilisation under Nitrogen Limitation Can Deplete Soil Carbon Stocks: Evidence from Swedish Meta-Replicated Long-Term Field Experiments. *Biogeosciences* **2016**, *13*, 1119–1127. [CrossRef]
63. Canadell, J.G.; Schulze, E.D. Global Potential of Biospheric Carbon Management for Climate Mitigation. *Nat. Commun.* **2014**, *5*. [CrossRef] [PubMed]
64. Dickie, A.; Streck, C.; Roe, S.; Zurek, M.; Haupt, F.; Dolginow, A. Strategies for Mitigating Climate Change in Agriculture: Recommendations for Philanthropy—Executive Summary. In *Climate Focus and California Environmental Associates, Prepared with the Support of the Climate and Land Use Alliance*; IPCC: Geneva, Switzerland, 2014.
65. Huang, T.; Ju, X.; Yang, H. Nitrate Leaching in a Winter Wheat-Summer Maize Rotation on a Calcareous Soil as Affected by Nitrogen and Straw Management. *Sci. Rep.* **2017**, *7*, 42247. [CrossRef]
66. Schlesinger, W.H.; Amundson, R. Managing for Soil Carbon Sequestration: Let's Get Realistic. *Glob. Chang. Biol.* **2019**, *25*, 386–389. [CrossRef] [PubMed]
67. Li, X.-M.; Chen, Q.-L.; He, C.; Shi, Q.; Chen, S.-C.; Reid, B.J.; Zhu, Y.-G.; Sun, G.-X. Organic Carbon Amendments Affect the Chemodiversity of Soil Dissolved Organic Matter and Its Associations with Soil Microbial Communities. *Environ. Sci. Technol.* **2019**, *53*, 50–59. [CrossRef] [PubMed]
68. Jacobs, A.; Poeplau, C.; Weiser, C.; Fahrion-Nitschke, A.; Don, A. Exports and Inputs of Organic Carbon on Agricultural Soils in Germany. *Nutr. Cycl. Agroecosystems* **2020**, *118*, 249–271. [CrossRef]
69. Mathew, I.; Shimelis, H.; Mutema, M.; Minasny, B.; Chaplot, V. Crops for Increasing Soil Organic Carbon Stocks—A Global Meta Analysis. *Geoderma* **2020**, *367*, 114230. [CrossRef]
70. Sykes, A.J.; Macleod, M.; Eory, V.; Rees, R.M.; Payen, F.; Myrgiotis, V.; Williams, M.; Sohi, S.; Hillier, J.; Moran, D.; et al. Characterising the Biophysical, Economic and Social Impacts of Soil Carbon Sequestration as a Greenhouse Gas Removal Technology. *Glob. Chang. Biol.* **2020**, *26*, 1085–1108. [CrossRef] [PubMed]
71. Maillard, É.; Angers, D.A. Animal Manure Application and Soil Organic Carbon Stocks: A Meta-Analysis. *Glob. Chang. Biol.* **2014**, *20*, 666–679. [CrossRef]
72. Wiesmeier, M.; Mayer, S.; Burmeister, J.; Hübner, R.; Kögel-Knabner, I. Feasibility of the 4 per 1000 Initiative in Bavaria: A Reality Check of Agricultural Soil Management and Carbon Sequestration Scenarios. *Geoderma* **2020**, *369*, 114333. [CrossRef]
73. Powlson, D.S.; Stirling, C.M.; Jat, M.L.; Gerard, B.G.; Palm, C.A.; Sanchez, P.A.; Cassman, K.G. Limited Potential of No-till Agriculture for Climate Change Mitigation. *Nat. Clim. Chang.* **2014**, *4*, 678–683. [CrossRef]
74. Bolan, N.S.; Adriano, D.C.; Kunhikrishnan, A.; James, T.; McDowell, R.; Senesi, N. Dissolved Organic Matter. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2011; Volume 110, pp. 1–75, ISBN 978-0-12-385531-2.
75. Shahbaz, M.; Kumar, A.; Kuzyakov, Y.; Börjesson, G.; Blagodatskaya, E. Interactive Priming Effect of Labile Carbon and Crop Residues on SOM Depends on Residue Decomposition Stage: Three-Source Partitioning to Evaluate Mechanisms. *Soil Biol. Biochem.* **2018**, *126*, 179–190. [CrossRef]
76. Hu, T.; Sørensen, P.; Olesen, J.E. Soil Carbon Varies between Different Organic and Conventional Management Schemes in Arable Agriculture. *Eur. J. Agron.* **2018**, *94*, 79–88. [CrossRef]
77. Zavattaro, L.; Bechini, L.; Grignani, C.; van Evert, F.K.; Mallast, J.; Spiegel, H.; Sandén, T.; Pecio, A.; Giráldez Cervera, J.V.; Guzmán, G.; et al. Agronomic Effects of Bovine Manure: A Review of Long-Term European Field Experiments. *Eur. J. Agron.* **2017**, *90*, 127–138. [CrossRef]

78. Powlson, D.S.; Glendining, M.J.; Coleman, K.; Whitmore, A.P. Implications for Soil Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agron. J.* **2011**, *103*, 279–287. [CrossRef]
79. Martínez-Blanco, J.; Lazcano, C.; Christensen, T.H.; Muñoz, P.; Rieradevall, J.; Møller, J.; Antón, A.; Boldrin, A. Compost Benefits for Agriculture Evaluated by Life Cycle Assessment. A Review. *Agron. Sustain. Dev.* **2013**, *33*, 721–732. [CrossRef]
80. Zavattaro, L.; Costamagna, C.; Grignani, C.; Bechini, L. Impacts of Soil Management on Productivity. Catch-C Deliverable D3.324. Available online: http://www.catch-c.eu/deliverables/WP3%20Task%203.2%20Productivity_D3.324_fin.pdf (accessed on 23 September 2020).
81. Lehtinen, T.; Dersch, G.; Söllinger, J.; Baumgarten, A.; Schlatter, N.; Aichberger, K.; Spiegel, H. Long-Term Amendment of Four Different Compost Types on a Loamy Silt Cambisol: Impact on Soil Organic Matter, Nutrients and Yields. *Arch. Agron. Soil Sci.* **2017**, *63*, 663–673. [CrossRef]
82. Lashermes, G.; Nicolardot, B.; Parnaudeau, V.; Thuriès, L.; Chaussod, R.; Guillotin, M.L.; Linères, M.; Mary, B.; Metzger, L.; Morvan, T.; et al. Indicator of Potential Residual Carbon in Soils after Exogenous Organic Matter Application. *Eur. J. Soil Sci.* **2009**, *60*, 297–310. [CrossRef]
83. Tiefenbacher, A.; Weigelhofer, G.; Klik, A.; Pucher, M.; Santner, J.; Wenzel, W.; Eder, A.; Strauss, P. Short-Term Effects of Fertilization on Dissolved Organic Matter in Soil Leachate. *Water* **2020**, *12*, 1617. [CrossRef]
84. Herrero, M.; Henderson, B.; Havlík, P.; Thornton, P.K.; Conant, R.T.; Smith, P.; Wirsenius, S.; Hristov, A.N.; Gerber, P.; Gill, M.; et al. Greenhouse Gas Mitigation Potentials in the Livestock Sector. *Nat. Clim. Chang.* **2016**, *6*, 452–461. [CrossRef]
85. Bronick, C.J.; Lal, R. Soil Structure and Management: A Review. *Geoderma* **2005**, *124*, 3–22. [CrossRef]
86. Lehtinen, T.; Schlatter, N.; Baumgarten, A.; Bechini, L.; Krüger, J.; Grignani, C.; Zavattaro, L.; Costamagna, C.; Spiegel, H. Effect of Crop Residue Incorporation on Soil Organic Carbon and Greenhouse Gas Emissions in European Agricultural Soils. *Soil Use Manag.* **2014**, *30*, 524–538. [CrossRef]
87. Trajanov, A.; Spiegel, H.; Debeljak, M.; Sandén, T. Using Data Mining Techniques to Model Primary Productivity from International Long-Term Ecological Research (ILTER) Agricultural Experiments in Austria. *Reg. Environ. Chang.* **2019**, *19*, 325–337. [CrossRef]
88. Soane, B.D.; Ball, B.C.; Arvidsson, J.; Basch, G.; Moreno, F.; Roger-Estrade, J. No-till in Northern, Western and South-Western Europe: A Review of Problems and Opportunities for Crop Production and the Environment. *Soil Tillage Res.* **2012**, *118*, 66–87. [CrossRef]
89. Chen, J.; Heiling, M.; Resch, C.; Mbaye, M.; Gruber, R.; Dercon, G. Does Maize and Legume Crop Residue Mulch Matter in Soil Organic Carbon Sequestration? *Agric. Ecosyst. Environ.* **2018**, *265*, 123–131. [CrossRef]
90. Hansen, S.; Berland Frøseth, R.; Stenberg, M.; Stalenga, J.; Olesen, J.E.; Krauss, M.; Radzikowski, P.; Doltra, J.; Nadeem, S.; Torp, T.; et al. Reviews and Syntheses: Review of Causes and Sources of N2O emissions and NO3 Leaching from Organic Arable Crop Rotations. *Biogeosciences* **2019**, *16*, 2795–2819. [CrossRef]
91. Wiesmeier, M.; Hübner, R.; Kögel-Knabner, I. Stagnating Crop Yields: An Overlooked Risk for the Carbon Balance of Agricultural Soils? *Sci. Total Environ.* **2015**, *536*, 1045–1051. [CrossRef] [PubMed]
92. Zhang, H.; Goll, D.S.; Manzoni, S.; Ciais, P.; Guenet, B.; Huang, Y. Modeling the Effects of Litter Stoichiometry and Soil Mineral N Availability on Soil Organic Matter Formation Using CENTURY-CUE (v1.0). *Geosci. Model Dev.* **2018**, *11*, 4779–4796. [CrossRef]
93. Wang, B.; Liu, C.; Chen, Y.; Dong, F.; Chen, S.; Zhang, D.; Zhu, J. Structural Characteristics, Analytical Techniques and Interactions with Organic Contaminants of Dissolved Organic Matter Derived from Crop Straw: A Critical Review. *RSC Adv.* **2018**, *8*, 36927–36938. [CrossRef]
94. Poeplau, C.; Don, A. Carbon Sequestration in Agricultural Soils via Cultivation of Cover Crops—A Meta-Analysis. *Agric. Ecosyst. Environ.* **2015**, *200*, 33–41. [CrossRef]
95. Tellez-Rio, A.; Vallejo, A.; García-Marco, S.; Martin-Lammerding, D.; Tenorio, J.L.; Rees, R.M.; Guardia, G. Conservation Agriculture Practices Reduce the Global Warming Potential of Rainfed Low N Input Semi-Arid Agriculture. *Eur. J. Agron.* **2017**, *84*, 95–104. [CrossRef]
96. Wesseler, J.; Drabik, D. Prices Matter: Analysis of Food and Energy Competition Relative to Land Resources in the European Union. *NJAS Wagening. J. Life Sci.* **2016**, *77*, 19–24. [CrossRef]
97. Raich, J.W.; Potter, C.S. Global Patterns of Carbon Dioxide Emissions from Soils. *Glob. Biogeochem. Cycles* **1995**, *9*, 23–36. [CrossRef]
98. Ostle, N.; Whiteley, A.S.; Bailey, M.J.; Sleep, D.; Ineson, P.; Manefield, M. Active Microbial RNA Turnover in a Grassland Soil Estimated Using a 13CO2 Spike. *Soil Biol. Biochem.* **2003**, *35*, 877–885. [CrossRef]
99. Kuzyakov, Y.; Domanski, G. Carbon Input by Plants into the Soil. Review. *J. Plant Nutr. Soil Sci.* **2000**, *163*, 421–431. [CrossRef]
100. Wang, C.; Guo, L.; Li, Y.; Wang, Z. Systematic Comparison of C3 and C4 Plants Based on Metabolic Network Analysis. *BMC Syst. Biol.* **2012**, *6*, S9. [CrossRef] [PubMed]
101. Gherardi, L.A.; Sala, O.E. Global Patterns and Climatic Controls of Belowground Net Carbon Fixation. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 20038–20043. [CrossRef] [PubMed]
102. Kätterer, T.; Bolinder, M.A.; Andrén, O.; Kirchmann, H.; Menichetti, L. Roots Contribute More to Refractory Soil Organic Matter than Above-Ground Crop Residues, as Revealed by a Long-Term Field Experiment. *Agric. Ecosyst. Environ.* **2011**, *141*, 184–192. [CrossRef]
103. Xu, H.; Vandecasteele, B.; Zavattaro, L.; Sacco, D.; Wendland, M.; Boeckx, P.; Haesaert, G.; Sleutel, S. Maize Root-derived C in Soil and the Role of Physical Protection on Its Relative Stability over Shoot-derived C. *Eur. J. Soil Sci.* **2019**. [CrossRef]

104. Hu, T.; Sørensen, P.; Wahlström, E.M.; Chirinda, N.; Sharif, B.; Li, X.; Olesen, J.E. Root Biomass in Cereals, Catch Crops and Weeds Can Be Reliably Estimated without Considering Aboveground Biomass. *Agric. Ecosyst. Environ.* **2018**, *251*, 141–148. [CrossRef]
105. Kaiser, K.; Kalbitz, K. Cycling Downwards–Dissolved Organic Matter in Soils. *Soil Biol. Biochem.* **2012**, *52*, 29–32. [CrossRef]
106. Jarecki, M.K.; Lal, R. Crop Management for Soil Carbon Sequestration. *Crit. Rev. Plant Sci.* **2003**, *22*, 471–502. [CrossRef]
107. Finney, D.M.; Kaye, J.P. Functional Diversity in Cover Crop Polycultures Increases Multifunctionality of an Agricultural System. *J. Appl. Ecol.* **2017**, *54*, 509–517. [CrossRef]
108. Tiemann, L.K.; Grandy, A.S.; Atkinson, E.E.; Marin-Spiotta, E.; McDaniel, M.D. Crop Rotational Diversity Enhances Belowground Communities and Functions in an Agroecosystem. *Ecol. Lett.* **2015**, *18*, 761–771. [CrossRef]
109. Bolinder, M.A.; Kätterer, T.; Andrén, O.; Parent, L.E. Estimating Carbon Inputs to Soil in Forage-Based Crop Rotations and Modeling the Effects on Soil Carbon Dynamics in a Swedish Long-Term Field Experiment. *Can. J. Soil Sci.* **2012**, *92*, 821–833. [CrossRef]
110. Tidåker, P.; Sundberg, C.; Öborn, I.; Kätterer, T.; Bergkvist, G. Rotational Grass/Clover for Biogas Integrated with Grain Production–A Life Cycle Perspective. *Agric. Syst.* **2014**, *129*, 133–141. [CrossRef]
111. West, T.O.; Post, W.M. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1930–1946. [CrossRef]
112. Börjesson, G.; Bolinder, M.A.; Kirchmann, H.; Kätterer, T. Organic Carbon Stocks in Topsoil and Subsoil in Long-Term Ley and Cereal Monoculture Rotations. *Biol. Fertil. Soils* **2018**, *54*, 549–558. [CrossRef]
113. Sokol, N.W.; Kuebbing, S.E.; Karlsen-Ayala, E.; Bradford, M.A. Evidence for the Primacy of Living Root Inputs, Not Root or Shoot Litter, in Forming Soil Organic Carbon. *New Phytol.* **2019**, *221*, 233–246. [CrossRef] [PubMed]
114. Kutschera, L. *Wurzelatlas, mitteleuropäischer Ackerunkräuter und Kulturpflanzen*; Band 1; DLG Verlags GmbH: Frankfurt, Germany, 2010; ISBN 978-3-7690-0758-8.
115. Thorup-Kristensen, K.; Halberg, N.; Nicolaisen, M.; Olesen, J.E.; Crews, T.E.; Hinsinger, P.; Kirkegaard, J.; Pierret, A.; Dresbøll, D.B. Digging Deeper for Agricultural Resources, the Value of Deep Rooting. *Trends Plant Sci.* **2020**, *25*, 406–417. [CrossRef]
116. Poeplau, C.; Bolinder, M.A.; Eriksson, J.; Lundblad, M.; Kätterer, T. Positive Trends in Organic Carbon Storage in Swedish Agricultural Soils Due to Unexpected Socio-Economic Drivers. *Biogeosciences* **2015**, *12*, 3241–3251. [CrossRef]
117. Poffenbarger, H.J.; Olk, D.C.; Cambardella, C.; Kersey, J.; Liebman, M.; Mallarino, A.; Six, J.; Castellano, M.J. Whole-Profile Soil Organic Matter Content, Composition, and Stability under Cropping Systems That Differ in Belowground Inputs. *Agric. Ecosyst. Environ.* **2020**, *291*, 106810. [CrossRef]
118. Lugato, E.; Leip, A.; Jones, A. Mitigation Potential of Soil Carbon Management Overestimated by Neglecting N2O Emissions. *Nat. Clim. Chang.* **2018**, *8*, 219–223. [CrossRef]
119. Lynch, J.P.; Wojciechowski, T. Opportunities and Challenges in the Subsoil: Pathways to Deeper Rooted Crops. *J. Exp. Bot.* **2015**, *66*, 2199–2210. [CrossRef] [PubMed]
120. Zhu, Y.; Weiner, J.; Yu, M.; Li, F. Evolutionary Agroecology: Trends in Root Architecture during Wheat Breeding. *Evol. Appl.* **2019**, *12*, 733–743. [CrossRef]
121. Chahal, I.; Vyn, R.J.; Mayers, D.; Van Eerd, L.L. Cumulative Impact of Cover Crops on Soil Carbon Sequestration and Profitability in a Temperate Humid Climate. *Sci. Rep.* **2020**, *10*. [CrossRef] [PubMed]
122. Kanders, M.J.; Berendonk, C.; Fritz, C.; Watson, C.; Wichern, F. Catch Crops Store More Nitrogen Below-Ground When Considering Rhizodeposits. *Plant Soil* **2017**, *417*, 287–299. [CrossRef]
123. Shackelford, G.E.; Kelsey, R.; Dicks, L.V. Effects of Cover Crops on Multiple Ecosystem Services: Ten Meta-Analyses of Data from Arable Farmland in California and the Mediterranean. *Land Use Policy* **2019**, *88*, 104204. [CrossRef]
124. Strickland, M.S.; Thomason, W.E.; Avera, B.; Franklin, J.; Minick, K.; Yamada, S.; Badgley, B.D. Short-Term Effects of Cover Crops on Soil Microbial Characteristics and Biogeochemical Processes across Actively Managed Farms. *Agrosystems Geosci. Environ.* **2019**, *2*, 1–9. [CrossRef]
125. Abdalla, M.; Hastings, A.; Cheng, K.; Yue, Q.; Chadwick, D.; Espenberg, M.; Truu, J.; Rees, R.M.; Smith, P. A Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity. *Glob. Chang. Biol.* **2019**, *25*, 2530–2543. [CrossRef]
126. Dabney, S.M.; Delgado, J.A.; Reeves, D.W. Using Winter Cover Crops to Improve Soil and Water Quality. *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 1221–1250. [CrossRef]
127. Koehler-Cole, K.; Elmore, R.W. Seeding Rates and Productivity of Broadcast Interseeded Cover Crops. *Agronomy* **2020**, *10*, 1723. [CrossRef]
128. Lawson, A.; Cogger, C.; Bary, A.; Fortuna, A.-M. Influence of Seeding Ratio, Planting Date, and Termination Date on Rye-Hairy Vetch Cover Crop Mixture Performance under Organic Management. *PLoS ONE* **2015**, *10*, e0129597. [CrossRef]
129. Bleuler, M.; Farina, R.; Francaviglia, R.; di Bene, C.; Napoli, R.; Marchetti, A. Modelling the Impacts of Different Carbon Sources on the Soil Organic Carbon Stock and CO 2 Emissions in the Foggia Province (Southern Italy). *Agric. Syst.* **2017**, *157*, 258–268. [CrossRef]
130. Chambers, A.; Lal, R.; Paustian, K. Soil Carbon Sequestration Potential of US Croplands and Grasslands: Implementing the 4 per Thousand Initiative. *J. Soil Water Conserv.* **2016**, *71*, 68A–74A. [CrossRef]
131. Jian, J.; Du, X.; Reiter, M.S.; Stewart, R.D. A Meta-Analysis of Global Cropland Soil Carbon Changes Due to Cover Cropping. *Soil Biol. Biochem.* **2020**, *143*, 107735. [CrossRef]

132. Northup, R.R.; Dahlgren, R.A.; McColl, J.G. Polyphenols as Regulators of Plant-Litter-Soil Interactions in Northern California's Pygmy Forest: A Positive Feedback? *Biogeochemistry* **1998**, *42*, 189–220. [CrossRef]
133. White, K.E.; Brennan, E.B.; Cavigelli, M.A.; Smith, R.F. Winter Cover Crops Increase Readily Decomposable Soil Carbon, but Compost Drives Total Soil Carbon during Eight Years of Intensive, Organic Vegetable Production in California. *PLoS ONE* **2020**, *15*, e0228677. [CrossRef] [PubMed]
134. Wille, L.; Messmer, M.M.; Studer, B.; Hohmann, P. Insights to Plant-Microbe Interactions Provide Opportunities to Improve Resistance Breeding against Root Diseases in Grain Legumes: Microbe-Supported Resistance Breeding in Legumes. *Plant Cell Environ.* **2019**, *42*, 20–40. [CrossRef] [PubMed]
135. Bodner, G.; Mentler, A.; Klik, A.; Kaul, H.-P.; Zechmeister-Boltenstern, S. Do Cover Crops Enhance Soil Greenhouse Gas Losses during High Emission Moments under Temperate Central Europe Conditions? *Die Bodenkult. J. Land Manag. Food Environ.* **2018**, *68*, 171–187. [CrossRef]
136. Dignac, M.-F.; Derrien, D.; Barré, P.; Barot, S.; Cécillon, L.; Chenu, C.; Chevallier, T.; Freschet, G.T.; Garnier, P.; Guenet, B.; et al. Increasing Soil Carbon Storage: Mechanisms, Effects of Agricultural Practices and Proxies. A Review. *Agron. Sustain. Dev.* **2017**, *37*. [CrossRef]
137. De Clercq, T.; Heiling, M.; Dercon, G.; Resch, C.; Aigner, M.; Mayer, L.; Mao, Y.; Elsen, A.; Steier, P.; Leifeld, J.; et al. Predicting Soil Organic Matter Stability in Agricultural Fields through Carbon and Nitrogen Stable Isotopes. *Soil Biol. Biochem.* **2015**, *88*, 29–38. [CrossRef]
138. Six, J.; Elliott, E.T.; Paustian, K. Soil Macroaggregate Turnover and Microaggregate Formation: A Mechanism for C Sequestration under No-Tillage Agriculture. *Soil Biol. Biochem.* **2000**, *32*, 2099–2103. [CrossRef]
139. Veloso, M.G.; Cecagno, D.; Bayer, C. Legume Cover Crops under No-Tillage Favor Organomineral Association in Microaggregates and Soil C Accumulation. *Soil Tillage Res.* **2019**, *190*, 139–146. [CrossRef]
140. Beniston, J.W.; Shipitalo, M.J.; Lal, R.; Dayton, E.A.; Hopkins, D.W.; Jones, F.; Joynes, A.; Dungait, J.A.J. Carbon and Macronutrient Losses during Accelerated Erosion under Different Tillage and Residue Management: Soil C, N and P Losses during Erosion. *Eur. J. Soil Sci.* **2015**, *66*, 218–225. [CrossRef]
141. Mazzoncini, M.; Antichi, D.; Di Bene, C.; Risaliti, R.; Petri, M.; Bonari, E. Soil Carbon and Nitrogen Changes after 28 Years of No-Tillage Management under Mediterranean Conditions. *Eur. J. Agron.* **2016**, *77*, 156–165. [CrossRef]
142. Abid, M.; Lal, R. Tillage and Drainage Impact on Soil Quality: II. Tensile Strength of Aggregates, Moisture Retention and Water Infiltration. *Soil Tillage Res.* **2009**, *103*, 364–372. [CrossRef]
143. Mikha, M.M.; Rice, C.W. Tillage and Manure Effects on Soil and Aggregate-Associated Carbon and Nitrogen. *Soil Sci. Soc. Am. J.* **2004**, *68*, 809. [CrossRef]
144. Sanderman, J.; Farquharson, R.; Baldock, J.A. *Soil Carbon Sequestration Potential: A Review for Australian Agriculture*; CSIRO Land and Water, Australian Government: Canberra, Australia, 2010.
145. Luo, Z.; Wang, E.; Sun, O.J. Can No-Tillage Stimulate Carbon Sequestration in Agricultural Soils? A Meta-Analysis of Paired Experiments. *Agric. Ecosyst. Environ.* **2010**, *139*, 224–231. [CrossRef]
146. Ogle, S.M.; Alsaker, C.; Baldock, J.; Bernoux, M.; Breidt, F.J.; McConkey, B.; Regina, K.; Vazquez-Amabile, G.G. Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Sci. Rep.* **2019**, *9*, 11665. [CrossRef]
147. Haddaway, N.R.; Hedlund, K.; Jackson, L.E.; Kätterer, T.; Lugato, E.; Thomsen, I.K.; Jørgensen, H.B.; Isberg, P.-E. How Does Tillage Intensity Affect Soil Organic Carbon? A Systematic Review. *Environ. Evid.* **2017**, *6*. [CrossRef]
148. Valkama, E.; Kunypiyaeva, G.; Zhapayev, R.; Karabayev, M.; Zhusupbekov, E.; Perego, A.; Schillaci, C.; Sacco, D.; Moretti, B.; Grignani, C.; et al. Can Conservation Agriculture Increase Soil Carbon Sequestration? A Modelling Approach. *Geoderma* **2020**, *369*, 114298. [CrossRef]
149. Husniev, I.; Romanenkov, V.; Minakova, O.; Krasilnikov, P. Modelling and Prediction of Organic Carbon Dynamics in Arable Soils Based on a 62-Year Field Experiment in the Voronezh Region, European Russia. *Agronomy* **2020**, *10*, 1607. [CrossRef]
150. Virto, I.; Barré, P.; Burlot, A.; Chenu, C. Carbon Input Differences as the Main Factor Explaining the Variability in Soil Organic C Storage in No-Tilled Compared to Inversion Tilled Agrosystems. *Biogeochemistry* **2012**, *108*, 17–26. [CrossRef]
151. Williams, H.; Colombi, T.; Keller, T. The Influence of Soil Management on Soil Health: An on-Farm Study in Southern Sweden. *Geoderma* **2020**, *360*, 114010. [CrossRef]
152. Govaerts, B.; Verhulst, N.; Castellanos-Navarrete, A.; Sayre, K.D.; Dixon, J.; Dendooven, L. Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality. *Crit. Rev. Plant Sci.* **2009**, *28*, 97–122. [CrossRef]
153. Kassam, A.; Friedrich, T.; Derpsch, R. Global Spread of Conservation Agriculture. *Int. J. Environ. Stud.* **2019**, *76*, 29–51. [CrossRef]
154. Meurer, K.H.E.; Haddaway, N.R.; Bolinder, M.A.; Kätterer, T. Tillage Intensity Affects Total SOC Stocks in Boreo-Temperate Regions Only in the Topsoil—A Systematic Review Using an ESM Approach. *Earth Sci. Rev.* **2018**, *177*, 613–622. [CrossRef]
155. Spiegel, H.; Dersch, G.; Hösch, J.; Baumgarten, A. Tillage Effects on Soil Organic Carbon and Nutrientavailability in a Long-Term Field Experiment in Austria. *Die Bodenkult. J. Land Manag. Food Environ.* **2007**, *58*, 47–58.
156. Chauhan, B.S.; Gill, G.S.; Preston, C. Tillage System Effects on Weed Ecology, Herbicide Activity and Persistence: A Review. *Aust. J. Exp. Agric.* **2006**, *46*, 1557. [CrossRef]
157. Moitzi, G.; Neugschwandtner, R.W.; Kaul, H.-P.; Wagentristl, H. Energy Efficiency of Winter Wheat in a Long-Term Tillage Experiment under Pannonian Climate Conditions. *Eur. J. Agron.* **2019**, *103*, 24–31. [CrossRef]

158. Sanden, T.; Spiegel, H.; Stüger, H.-P.; Schlatter, N.; Haslmayr, H.-P.; Zavattaro, L.; Grignani, C.; Bechini, L.; D′Hose, T.; Molendijk, L.; et al. European Long-Term Field Experiments: Knowledge Gained about Alternative Management Practices. *Soil Use Manag.* **2018**, *34*, 167–176. [CrossRef]
159. Blanco-Canqui, H.; Francis, C.A.; Galusha, T.D. Does Organic Farming Accumulate Carbon in Deeper Soil Profiles in the Long Term? *Geoderma* **2017**, *288*, 213–221. [CrossRef]
160. Leifeld, J.; Fuhrer, J. Organic Farming and Soil Carbon Sequestration: What Do We Really Know About the Benefits? *AMBIO* **2010**, *39*, 585–599. [CrossRef]
161. Muller, A.; Bautze, L.; Meier, M.; Gattinger, A. *Organic Farming, Climate Change Mitigation and beyond—Reducing the Environmental Impacts of EU Agriculture*; IFOAM: Bonn, Germany, 2017.
162. Autret, B.; Beaudoin, N.; Rakotovololona, L.; Bertrand, M.; Grandeau, G.; Gréhan, E.; Ferchaud, F.; Mary, B. Can Alternative Cropping Systems Mitigate Nitrogen Losses and Improve GHG Balance? Results from a 19-Yr Experiment in Northern France. *Geoderma* **2019**, *342*, 20–33. [CrossRef]
163. Gattinger, A.; Muller, A.; Haeni, M.; Skinner, C.; Fliessbach, A.; Buchmann, N.; Mader, P.; Stolze, M.; Smith, P.; Scialabba, N.E.-H.; et al. Enhanced Top Soil Carbon Stocks under Organic Farming. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 18226–18231. [CrossRef]
164. Agrimonti, C.; Lauro, M.; Visioli, G. Smart Agriculture for Food Quality: Facing Climate Change in the 21st Century. *Crit. Rev. Food Sci. Nutr.* **2020**, 1–11. [CrossRef]
165. Bellarby, J.; Foereid, B.; Hastings, A.; Smith, P. *Cool Farming: Climate Impacts of Agriculture and Mitigation Potential*; University of Aberdeen/Greenpeace, Greenpace International: Amsterdam, The Netherlands, 2008.
166. Brückler, M.; Resl, T.; Reindl, A. Comparison of Organic and Conventional Crop Yields in Austria. *Die Bodenkult. J. Land Manag. Food Environ.* **2018**, *68*, 223–236. [CrossRef]
167. Montanarella, L.; Panagos, P. The Relevance of Sustainable Soil Management within the European Green Deal. *Land Use Policy* **2021**, *100*, 104950. [CrossRef]
168. Trost, B.; Prochnow, A.; Drastig, K.; Meyer-Aurich, A.; Ellmer, F.; Baumecker, M. Irrigation, Soil Organic Carbon and N2O Emissions. A Review. *Agron. Sustain. Dev.* **2013**, *33*, 733–749. [CrossRef]
169. Zhou, X.; Zhou, L.; Nie, Y.; Fu, Y.; Du, Z.; Shao, J.; Zheng, Z.; Wang, X. Similar Responses of Soil Carbon Storage to Drought and Irrigation in Terrestrial Ecosystems but with Contrasting Mechanisms: A Meta-Analysis. *Agric. Ecosyst. Environ.* **2016**, *228*, 70–81. [CrossRef]
170. Meena, R.S.; Kumar, S.; Yadav, G.S. Soil Carbon Sequestration in Crop Production. In *Nutrient Dynamics for Sustainable Crop Production*; Meena, R.S., Ed.; Springer: Singapore, 2020; pp. 1–39,q ISBN 9789811386596.
171. Hatfield, J.L.; Dold, C. Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Front. Plant Sci.* **2019**, *10*. [CrossRef]
172. Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liermann, C.R.; et al. Global Threats to Human Water Security and River Biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef]
173. Snyder, C.S.; Bruulsema, T.W.; Jensen, T.L.; Fixen, P.E. Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects. *Agric. Ecosyst. Environ.* **2009**, *133*, 247–266. [CrossRef]
174. Sohi, S.P. Carbon Storage with Benefits. *Science* **2012**, *338*, 1034–1035. [CrossRef] [PubMed]
175. Lehmann, J. A Handful of Carbon. *Nature* **2007**, *447*, 143–144. [CrossRef]
176. Ameloot, N.; De Neve, S.; Jegajeevagan, K.; Yildiz, G.; Buchan, D.; Funkuin, Y.N.; Prins, W.; Bouckaert, L.; Sleutel, S. Short-Term CO_2 and N_2O Emissions and Microbial Properties of Biochar Amended Sandy Loam Soils. *Soil Biol. Biochem.* **2013**, *57*, 401–410. [CrossRef]
177. Kuzyakov, Y. Priming Effects: Interactions between Living and Dead Organic Matter. *Soil Biol. Biochem.* **2010**, *42*, 1363–1371. [CrossRef]
178. Paetsch, L.; Mueller, C.W.; Kögel-Knabner, I.; von Lützow, M.; Girardin, C.; Rumpel, C. Effect of In-Situ Aged and Fresh Biochar on Soil Hydraulic Conditions and Microbial C Use under Drought Conditions. *Sci. Rep.* **2018**, *8*. [CrossRef]
179. Wardle, D.A.; Nilsson, M.-C.; Zackrisson, O. Fire-Derived Charcoal Causes Loss of Forest Humus. *Science* **2008**, *320*, 629. [CrossRef] [PubMed]
180. Novak, J.M.; Busscher, W.J.; Watts, D.W.; Laird, D.A.; Ahmedna, M.A.; Niandou, M.A.S. Short-Term CO2 Mineralization after Additions of Biochar and Switchgrass to a Typic Kandiudult. *Geoderma* **2010**, *154*, 281–288. [CrossRef]
181. (Han) Weng, Z.; Van Zwieten, L.; Singh, B.P.; Tavakkoli, E.; Joseph, S.; Macdonald, L.M.; Rose, T.J.; Rose, M.T.; Kimber, S.W.L.; Morris, S.; et al. Biochar Built Soil Carbon over a Decade by Stabilizing Rhizodeposits. *Nat. Clim. Chang.* **2017**, *7*, 371–376. [CrossRef]
182. Liu, Z.; Dugan, B.; Masiello, C.A.; Barnes, R.T.; Gallagher, M.E.; Gonnermann, H. Impacts of Biochar Concentration and Particle Size on Hydraulic Conductivity and DOC Leaching of Biochar–Sand Mixtures. *J. Hydrol.* **2016**, *533*, 461–472. [CrossRef]
183. Maestrini, B.; Nannipieri, P.; Abiven, S. A Meta-Analysis on Pyrogenic Organic Matter Induced Priming Effect. *GCB Bioenergy* **2015**, *7*, 577–590. [CrossRef]
184. Lorenz, K.; Lal, R. Soil Organic Carbon Sequestration in Agroforestry Systems. A Review. *Agron. Sustain. Dev.* **2014**, *34*, 443–454. [CrossRef]

185. Mao, J.-D.; Johnson, R.L.; Lehmann, J.; Olk, D.C.; Neves, E.G.; Thompson, M.L.; Schmidt-Rohr, K. Abundant and Stable Char Residues in Soils: Implications for Soil Fertility and Carbon Sequestration. *Environ. Sci. Technol.* **2012**, *46*, 9571–9576. [CrossRef]
186. Solomon, D.; Lehmann, J.; Wang, J.; Kinyangi, J.; Heymann, K.; Lu, Y.; Wirick, S.; Jacobsen, C. Micro- and Nano-Environments of C Sequestration in Soil: A Multi-Elemental STXM–NEXAFS Assessment of Black C and Organomineral Associations. *Sci. Total Environ.* **2012**, *438*, 372–388. [CrossRef]
187. Lorenz, K.; Lal, R. Biochar Application to Soil for Climate Change Mitigation by Soil Organic Carbon Sequestration. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 651–670. [CrossRef]
188. Rumpel, C.; Kögel-Knabner, I. Deep Soil Organic Matter—a Key but Poorly Understood Component of Terrestrial C Cycle. *Plant Soil* **2011**, *338*, 143–158. [CrossRef]
189. Liang, C.; Zhu, X.; Fu, S.; Méndez, A.; Gascó, G.; Paz-Ferreiro, J. Biochar Alters the Resistance and Resilience to Drought in a Tropical Soil. *Environ. Res. Lett.* **2014**, *9*, 064013. [CrossRef]
190. Palansooriya, K.N.; Ok, Y.S.; Awad, Y.M.; Lee, S.S.; Sung, J.-K.; Koutsospyros, A.; Moon, D.H. Impacts of Biochar Application on Upland Agriculture: A Review. *J. Environ. Manag.* **2019**, *234*, 52–64. [CrossRef] [PubMed]
191. Schmidt, H.-P.; Kammann, C.; Niggli, C.; Evangelou, M.W.H.; Mackie, K.A.; Abiven, S. Biochar and Biochar-Compost as Soil Amendments to a Vineyard Soil: Influences on Plant Growth, Nutrient Uptake, Plant Health and Grape Quality. *Agric. Ecosyst. Environ.* **2014**, *191*, 117–123. [CrossRef]
192. Rechberger, M.V.; Kloss, S.; Wang, S.-L.; Lehmann, J.; Rennhofer, H.; Ottner, F.; Wriessnig, K.; Daudin, G.; Lichtenegger, H.; Soja, G.; et al. Enhanced Cu and Cd Sorption after Soil Aging of Woodchip-Derived Biochar: What Were the Driving Factors? *Chemosphere* **2019**, *216*, 463–471. [CrossRef] [PubMed]
193. Majumder, S.; Neogi, S.; Dutta, T.; Powel, M.A.; Banik, P. The Impact of Biochar on Soil Carbon Sequestration: Meta-Analytical Approach to Evaluating Environmental and Economic Advantages. *J. Environ. Manag.* **2019**, *250*, 109466. [CrossRef]
194. Smith, P. Soil Carbon Sequestration and Biochar as Negative Emission Technologies. *Glob. Chang. Biol.* **2016**, *22*, 1315–1324. [CrossRef]
195. Woolf, D.; Amonette, J.E.; Street-Perrott, F.A.; Lehmann, J.; Joseph, S. Sustainable Biochar to Mitigate Global Climate Change. *Nat. Commun.* **2010**, *1*. [CrossRef]
196. Leng, L.; Huang, H.; Li, H.; Li, J.; Zhou, W. Biochar Stability Assessment Methods: A Review. *Sci. Total Environ.* **2019**, *647*, 210–222. [CrossRef]
197. Rizwan, M.; Ali, S.; Qayyum, M.F.; Ibrahim, M.; Zia-ur-Rehman, M.; Abbas, T.; Ok, Y.S. Mechanisms of Biochar-Mediated Alleviation of Toxicity of Trace Elements in Plants: A Critical Review. *Environ. Sci. Pollut. Res.* **2016**, *23*, 2230–2248. [CrossRef]
198. Shi, L.; Feng, W.; Xu, J.; Kuzyakov, Y. Agroforestry Systems: Meta-Analysis of Soil Carbon Stocks, Sequestration Processes, and Future Potentials. *Land Degrad. Dev.* **2018**, *29*, 3886–3897. [CrossRef]
199. Sun, H.; Koal, P.; Gerl, G.; Schroll, R.; Gattinger, A.; Joergensen, R.G.; Munch, J.C. Microbial Communities and Residues in Robinia- and Poplar-Based Alley-Cropping Systems under Organic and Integrated Management. *Agrofor. Syst.* **2018**, *92*, 35–46. [CrossRef]
200. Cardinael, R.; Umulisa, V.; Toudert, A.; Olivier, A.; Bockel, L.; Bernoux, M. Revisiting IPCC Tier 1 Coefficients for Soil Organic and Biomass Carbon Storage in Agroforestry Systems. *Environ. Res. Lett.* **2018**, *13*, 124020. [CrossRef]
201. Lal, R.; Smith, P.; Jungkunst, H.F.; Mitsch, W.J.; Lehmann, J.; Nair, P.K.R.; McBratney, A.B.; de Moraes Sá, J.C.; Schneider, J.; Zinn, Y.L.; et al. The Carbon Sequestration Potential of Terrestrial Ecosystems. *J. Soil Water Conserv.* **2018**, *73*, 145A–152A. [CrossRef]
202. Soussana, J.F.; Lutfalla, S.; Ehrhardt, F.; Rosenstock, T.; Lamanna, C.; Havlík, P.; Richards, M.; Chotte, J.L.; Torquebiau, E.; Ciais, P.; et al. Matching Policy and Science: Rationale for the '4 per 1000-Soils for Food Security and Climate' Initiative. *Soil Tillage Res.* **2019**, *188*, 3–15. [CrossRef]
203. Liebhard, P.; Spiegel, H. Effects of long term cultivation of Miscanthus Giganteus on selected chemical and physicalparameters. In Proceedings of the Ernähren uns in der Zukunft Energiepflanzen? Raumberg-Gumpenstein, Austria, 26 May 2008.
204. Chimento, C.; Almagro, M.; Amaducci, S. Carbon Sequestration Potential in Perennial Bioenergy Crops: The Importance of Organic Matter Inputs and Its Physical Protection. *GCB Bioenergy* **2016**, *8*, 111–121. [CrossRef]
205. Kalt, G.; Mayer, A.; Theurl, M.C.; Lauk, C.; Erb, K.; Haberl, H. Natural Climate Solutions versus Bioenergy: Can Carbon Benefits of Natural Succession Compete with Bioenergy from Short Rotation Coppice? *GCB Bioenergy* **2019**, *11*, 1283–1297. [CrossRef]
206. Winiwarter, V.; Gerzabek, M.H. (Eds.) *The Challenge of Sustaining Soils: Natural and Social Ramifications of Biomass Production in a Changing World*; Interdisciplinary Perspectives; Verlag der Österreichischen Akadademie der Wissenschaften: Wien, Austria, 2012; ISBN 978-3-7001-7212-3.
207. Paradelo, R.; Virto, I.; Chenu, C. Net Effect of Liming on Soil Organic Carbon Stocks: A Review. *Agric. Ecosyst. Environ.* **2015**, *202*, 98–107. [CrossRef]
208. Briedis, C.; Moraes Sá, J.C.; Caires, E.F.; Fátima Navarro, J.; Inagaki, T.M.; Boer, A.; Oliveira Ferreira, A.; Neto, C.Q.; Canalli, L.B.; Santos, J.B. Changes in Organic Matter Pools and Increases in Carbon Sequestration in Response to Surface Liming in an Oxisol under Long-Term No-Till. *Soil Sci. Soc. Am. J.* **2012**, *76*, 151–160. [CrossRef]
209. Kowalenko, C.G.; Ihnat, M. Residual Effects of Combinations of Limestone, Zinc and Manganese Applications on Soil and Plant Nutrients under Mild and Wet Climatic Conditions. *Can. J. Soil Sci.* **2013**, *93*, 113–125. [CrossRef]
210. Beerling, D.J.; Leake, J.R.; Long, S.P.; Scholes, J.D.; Ton, J.; Nelson, P.N.; Bird, M.; Kantzas, E.; Taylor, L.L.; Sarkar, B.; et al. Farming with Crops and Rocks to Address Global Climate, Food and Soil Security. *Nat. Plants* **2018**, *4*, 138–147. [CrossRef]

211. Shao, S.; Driscoll, C.T.; Johnson, C.E.; Fahey, T.J.; Battles, J.J.; Blum, J.D. Long-Term Responses in Soil Solution and Stream-Water Chemistry at Hubbard Brook after Experimental Addition of Wollastonite. *Environ. Chem.* **2016**, *13*, 528. [CrossRef]
212. Marschner, H.; Marschner, P. (Eds.) *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Elsevier/Academic Press: London, UK; Elsevier/Academic Press: Waltham, MA, USA, 2012; ISBN 978-0-12-384905-2.
213. Kane, D. *Carbon Sequestration Potential on Agricultural Lands: A Review of Current Sci-Ence and Available Practices*; National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC: Washington, DC, USA, 2015.
214. Barré, P.; Eglin, T.; Christensen, B.T.; Ciais, P.; Houot, S.; Kätterer, T.; van Oort, F.; Peylin, P.; Poulton, P.R.; Romanenkov, V.; et al. Long-Term Bare Fallow Experiments Offer New Opportunities for the Quantification and the Study of Stable Carbon in Soil. *Biogeosci. Discuss.* **2010**, *7*, 4887–4917. [CrossRef]
215. Keel, S.G.; Anken, T.; Büchi, L.; Chervet, A.; Fliessbach, A.; Flisch, R.; Huguenin-Elie, O.; Mäder, P.; Mayer, J.; Sinaj, S.; et al. Loss of Soil Organic Carbon in Swiss Long-Term Agricultural Experiments over a Wide Range of Management Practices. *Agric. Ecosyst. Environ.* **2019**, *286*, 106654. [CrossRef]
216. Taghizadeh-Toosi, A.; Olesen, J.E. Modelling Soil Organic Carbon in Danish Agricultural Soils Suggests Low Potential for Future Carbon Sequestration. *Agric. Syst.* **2016**, *145*, 83–89. [CrossRef]
217. Wang, S.; Zhao, Y.; Wang, J.; Zhu, P.; Cui, X.; Han, X.; Xu, M.; Lu, C. The Efficiency of Long-Term Straw Return to Sequester Organic Carbon in Northeast China's Cropland. *J. Integr. Agric.* **2018**, *17*, 436–448. [CrossRef]
218. Smith, P.; Fang, C.; Dawson, J.J.C.; Moncrieff, J.B. Impact of Global Warming on Soil Organic Carbon. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2008; Volume 97, pp. 1–43, ISBN 978-0-12-374352-7.
219. Aaltonen, H.; Palviainen, M.; Zhou, X.; Köster, E.; Berninger, F.; Pumpanen, J.; Köster, K. Temperature Sensitivity of Soil Organic Matter Decomposition after Forest Fire in Canadian Permafrost Region. *J. Environ. Manag.* **2019**, *241*, 637–644. [CrossRef] [PubMed]
220. Moinet, G.Y.K.; Hunt, J.E.; Kirschbaum, M.U.F.; Morcom, C.P.; Midwood, A.J.; Millard, P. The Temperature Sensitivity of Soil Organic Matter Decomposition Is Constrained by Microbial Access to Substrates. *Soil Biol. Biochem.* **2018**, *116*, 333–339. [CrossRef]
221. Lai, L.; Huang, X.; Yang, H.; Chuai, X.; Zhang, M.; Zhong, T.; Chen, Z.; Chen, Y.; Wang, X.; Thompson, J.R. Carbon Emissions from Land-Use Change and Management in China between 1990 and 2010. *Sci. Adv.* **2016**, *2*, e1601063. [CrossRef]
222. Post, W.M.; Kwon, K.C. Soil Carbon Sequestration and Land-Use Change: Processes and Potential: Soil Carbon Sequestration and Land-Use Change. *Glob. Chang. Biol.* **2000**, *6*, 317–327. [CrossRef]
223. Guenet, B.; Camino-Serrano, M.; Ciais, P.; Tifafi, M.; Maignan, F.; Soong, J.L.; Janssens, I.A. Impact of Priming on Global Soil Carbon Stocks. *Glob. Chang. Biol.* **2018**, *24*, 1873–1883. [CrossRef]
224. Crowther, T.W.; Todd-Brown, K.E.O.; Rowe, C.W.; Wieder, W.R.; Carey, J.C.; Machmuller, M.B.; Snoek, B.L.; Fang, S.; Zhou, G.; Allison, S.D.; et al. Quantifying Global Soil Carbon Losses in Response to Warming. *Nature* **2016**, *540*, 104–108. [CrossRef] [PubMed]
225. Tiefenbacher, A.; Weigelhofer, G.; Klik, A.; Mabit, L.; Santner, J.; Wenzel, W.; Strauss, P. Antecedent Soil Moisture and Rain Intensity Control Pathways and Quality of Organic Carbon Exports from Arable Land. *CATENA* **2021**, *202*, 105297. [CrossRef]
226. Gardi, C. *Urban Expansion, Land Cover and Soil Ecosystem Services*; Routledge: New York, NY, USA, 2017; ISBN 978-1-317-50470-2.
227. Lu, C.; Kotze, D.J.; Setälä, H.M. Soil Sealing Causes Substantial Losses in C and N Storage in Urban Soils under Cool Climate. *Sci. Total Environ.* **2020**, *725*, 138369. [CrossRef] [PubMed]
228. Scalenghe, R.; Marsan, F.A. The Anthropogenic Sealing of Soils in Urban Areas. *Landsc. Urban Plan.* **2009**, *90*, 1–10. [CrossRef]
229. Aksoy, E.; Gregor, M.; Schröder, C.; Löhnertz, M.; Louwagie, G. Assessing and Analysing the Impact of Land Take Pressures on Arable Land. *Solid Earth* **2017**, *8*, 683–695. [CrossRef]
230. European Commission. *Directorate General for the Environment. Hard Surfaces, Hidden Costs: Searching for Alternatives to Land Take and Soil Sealing*; Publications Office: Luxembourg, 2013.
231. Ronchi, S.; Salata, S.; Arcidiacono, A.; Piroli, E.; Montanarella, L. Policy Instruments for Soil Protection among the EU Member States: A Comparative Analysis. *Land Use Policy* **2019**, *82*, 763–780. [CrossRef]
232. IPCC Summary for Policymakers. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Shukla, P.R., Skea, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Eds.; IPCC: Geneva, Switzerland, 2019.
233. Bmlrt, B.L. *Regionen und Tourismus Grüner Bericht 2020*; Bundesministerium für Landwirtschaft, Regionen und Tourismus (BMLRT): Vienna, Austria, 2020.
234. Springmann, M.; Clark, M.; Mason-D'Croz, D.; Wiebe, K.; Bodirsky, B.L.; Lassaletta, L.; de Vries, W.; Vermeulen, S.J.; Herrero, M.; Carlson, K.M.; et al. Options for Keeping the Food System within Environmental Limits. *Nature* **2018**, *562*, 519–525. [CrossRef]
235. Theurl, M.C.; Lauk, C.; Kalt, G.; Mayer, A.; Kaltenegger, K.; Morais, T.G.; Teixeira, R.F.M.; Domingos, T.; Winiwarter, W.; Erb, K.-H.; et al. Food Systems in a Zero-Deforestation World: Dietary Change Is More Important than Intensification for Climate Targets in 2050. *Sci. Total Environ.* **2020**, *735*, 139353. [CrossRef]
236. Ingram, J.; Dwyer, J.; Gaskell, P.; Mills, J.; de Wolf, P. Reconceptualising Translation in Agricultural Innovation: A Co-Translation Approach to Bring Research Knowledge and Practice Closer Together. *Land Use Policy* **2018**, *70*, 38–51. [CrossRef]

237. Ingram, J.; Mills, J.; Dibari, C.; Ferrise, R.; Ghaley, B.B.; Hansen, J.G.; Iglesias, A.; Karaczun, Z.; McVittie, A.; Merante, P.; et al. Communicating Soil Carbon Science to Farmers: Incorporating Credibility, Salience and Legitimacy. *J. Rural Stud.* **2016**, *48*, 115–128. [CrossRef]
238. Piñeiro, V.; Arias, J.; Dürr, J.; Elverdin, P.; Ibáñez, A.M.; Kinengyere, A.; Opazo, C.M.; Owoo, N.; Page, J.R.; Prager, S.D.; et al. A Scoping Review on Incentives for Adoption of Sustainable Agricultural Practices and Their Outcomes. *Nat. Sustain.* **2020**, *3*, 809–820. [CrossRef]
239. Ingram, J. Agricultural Transition: Niche and Regime Knowledge Systems' Boundary Dynamics. *Environ. Innov. Soc. Transit.* **2018**, *26*, 117–135. [CrossRef]