Available online at www.agrifarming.org

DOI: http://dx.doi.org/10.18782/2582-7146.324

ISSN: 2582 – 7146

Curr. Rese. Agri. Far. (2022) *3*(1), 34-41

Current Research in Agriculture and Farming

Review Article

Peer-Reviewed, Refereed, Open Access Journal

Carbon Sequestration in Agricultural Systems: Strategies for Climate Change Mitigation and Sustainable Farming

Ravikesh Kumar Pal[1*], Mandeep Kumar[2], Jitendra Kumar[3]

[1]Ph.D scholar Agronomy, Bihar Agricultural University, Sabour, Bhagalpur, Bihar

[2]Ph.D Reaserch Scholar, CSA University Kanpur

[3]Assistant Professor, Horticulture (Vegetable Science)

Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, UP

*Corresponding Author E-mail: rkpal9506@gmail.com

Received: 16.12.2021 | Revised: 27.01.2022 | Accepted: 10.02.2022

ABSTRACT

Carbon sequestration in agricultural systems has emerged as a key strategy for mitigating climate change while enhancing sustainable farming practices. This review highlights the role of conservation agriculture, agroforestry, cover cropping, crop residue management, biochar application, organic amendments, and integrated nutrient management in increasing soil organic carbon and reducing greenhouse gas emissions. It also examines the contribution of precision agriculture, climate-smart farming, and regenerative agricultural practices to long-term carbon storage and improved soil health. Furthermore, the chapter discusses challenges, policy interventions, and future research priorities for promoting carbon sequestration, ensuring resilient agricultural systems, environmental sustainability, food security, and enhanced ecosystem services worldwide.

Keywords: *Soil organic carbon; conservation agriculture; biochar; agroforestry; climate-smart farming.*

INTRODUCTION

Anthropogenic activities have raised atmospheric carbon dioxide (CO_2) concentrations from a pre-industrial value of about 280 ppm to over 415 ppm by 2022, with agriculture, forestry, and other land uses contributing roughly 22% of global greenhouse gas (GHG) emissions (IPCC, 2022). At the same time, the agricultural sector is uniquely positioned to reverse part of this trend: soils contain almost three times more carbon than the atmosphere and four times more than terrestrial vegetation, making them a critical lever in any credible climate strategy (FAO & ITPS, 2015). Carbon sequestration in agricultural systems—the long-term removal of atmospheric CO_2 into stable plant biomass, soil organic matter, and inorganic carbonates—has therefore moved from a peripheral concept to a centrepiece of sustainable land-management policy.

Cite this article: Pal, R. K., Kumar, M., & Kumar, J. (2022). Carbon Sequestration in Agricultural Systems: Strategies for Climate Change Mitigation and Sustainable Farming, *Curr. Rese. Agri. Far. 3*(6), 34-41. doi: http://dx.doi.org/10.18782/2582-7146.324

The international "4 per 1000" initiative, launched at COP21, proposed that an annual increase of 0.4% in global soil organic carbon (SOC) stocks could meaningfully offset anthropogenic emissions while improving soil health and food security (Minasny et al., 2017). Although this target has been debated, it crystallised scientific and policy attention on cropland and grassland soils as carbon sinks. Lal (2004) was among the first to quantify the global SOC sequestration potential at 0.4–1.2 Pg C year^{-1}, and subsequent meta-analyses have largely confirmed the magnitude of this opportunity while clarifying that benefits are highly context-dependent.

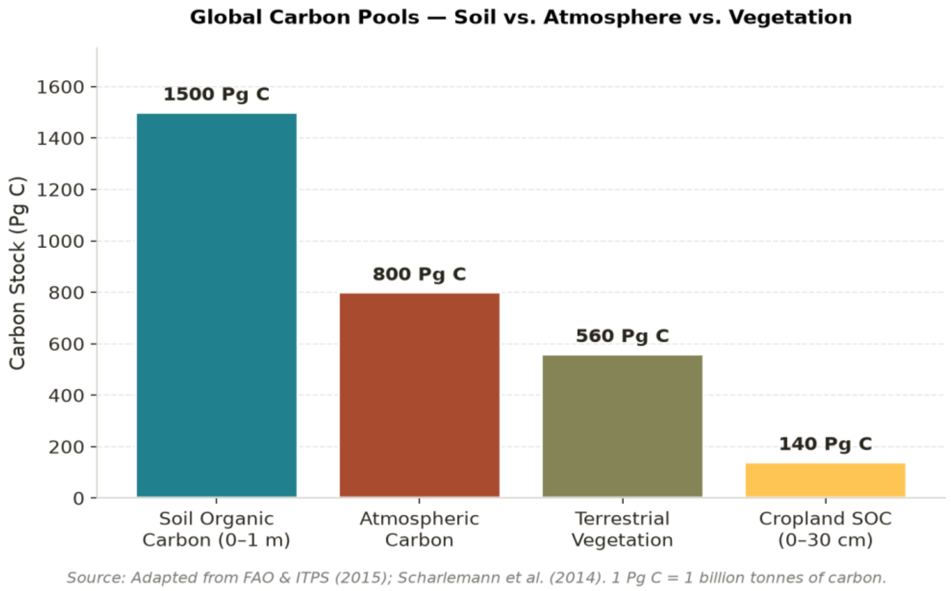


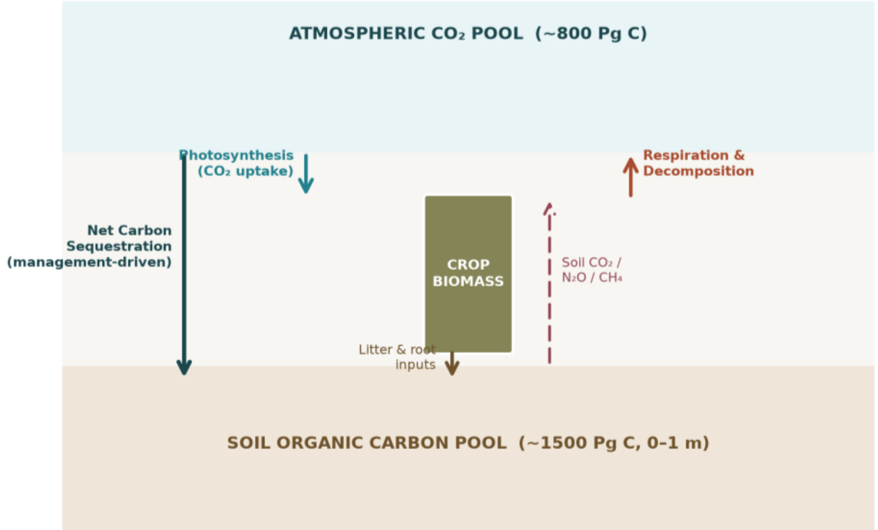
Figure1. Comparison of major global carbon pools (Pg C).

2. The Biogeochemical Basis of Agricultural Carbon Sequestration

Carbon sequestration in agricultural systems operates through two principal pathways: photosynthetic fixation into plant biomass and the subsequent stabilisation of carbon in soil organic matter, and the formation of secondary carbonates in arid and semi-arid soils. Of these, soil organic carbon dynamics dominate the mitigation conversation because of their magnitude, manageability, and rapid response to land-use change (Smith, 2016).

Soils receive carbon inputs from above-ground crop residues, root exudates, dead roots, manure, compost, and char products. These inputs are processed by microbial communities through cascading decomposition pathways that release a portion of carbon back to the atmosphere as CO_2 while stabilising a smaller fraction in mineral-associated organic matter and aggregate-protected pools (Cotrufo et al., 2019, as cited in Paustian et al., 2016). The net balance between input and mineralisation determines whether a soil acts as a carbon source or a sink. Paustian et al. (2016) emphasised that long-term stability depends less on the chemical recalcitrance of plant residues and more on physical occlusion within aggregates and chemical binding to mineral surfaces.

Historic agricultural expansion has caused significant SOC losses. A global assessment by Sanderman et al. (2017) estimated that cultivation has reduced topsoil carbon stocks by about 133 Pg over the past 12,000 years, with the steepest losses concentrated in the past two centuries. This "carbon debt" defines both the urgency of mitigation and the upper bound of restorative potential: soils that have lost carbon also retain the greatest capacity to regain it (Zomer et al., 2017).



Conceptual diagram adapted from Smith (2016) and Paustian et al. (2016).

Figure2. The agricultural carbon cycle: fluxes between atmosphere, plants, and soil

3. Key Management Strategies for Carbon Sequestration

3.1 Conservation tillage and no-till systems

Conventional tillage disrupts soil aggregates, accelerates microbial oxidation of organic matter, and exposes previously protected carbon to the atmosphere. Conservation tillage—particularly no-till with crop-residue retention—has therefore been promoted as a primary carbon-friendly practice. West and Post (2002) analysed 67 long-term experiments and reported a mean sequestration rate of approximately 0.57 Mg C ha^{-1} $year^{-1}$ following the conversion from conventional tillage to no-till. More recent global syntheses suggest a wider but generally lower range of 0.05–0.50 Mg C ha^{-1} $year^{-1}$, reflecting strong climate, soil texture, and depth-distribution effects (Powlson et al., 2014; Ogle et al., 2019). Notably, much of the apparent SOC gain under no-till is concentrated in the top 10–20 cm and may be partially offset by reduced carbon at greater depths, an issue Powlson et al. (2014) cautioned should temper optimism about no-till as a stand-alone solution.

3.2 Cover cropping and crop diversification

Cover crops planted between cash-crop cycles provide continuous photosynthetic input to the soil, reduce erosion, suppress weeds, and improve nutrient cycling. Poeplau and Don (2015) conducted a global meta-analysis of 37 studies and reported an average SOC sequestration rate of 0.32 Mg C ha^{-1} $year^{-1}$ in the top 22 cm of soil, with the effect being relatively constant across climates. Diversified crop rotations, especially those incorporating perennial legumes, further enhance carbon inputs while reducing reliance on synthetic nitrogen fertilisers that carry their own emission footprint (Smith, 2016).

Mixed cover-crop species combinations frequently outperform single-species treatments because complementary root architectures distribute carbon inputs across a wider soil profile. Legume–grass mixtures, in particular, supply biologically fixed nitrogen that supports microbial decomposition and aggregate formation while still delivering recalcitrant grass-root residues that contribute to long-term stable carbon pools (Poeplau & Don, 2015). When integrated into long crop rotations that include deep-rooted perennials such as alfalfa or pigeon pea, the cumulative SOC gain over a decade can exceed that achieved by any single annual practice (Smith, 2016).

3.3 Agroforestry systems

Agroforestry—the deliberate integration of trees and shrubs with crops or livestock—couples above-ground biomass accumulation with enhanced soil carbon inputs. Global syntheses indicate that agroforestry systems can sequester 0.30–1.40 Mg C ha^{-1} $year^{-1}$, with silvopastoral and shaded-perennial systems often at the upper end of this range

(Nair et al., 2010; & Zomer et al., 2016). Tropical homegardens, parkland systems in the Sahel, and shaded coffee or cocoa systems in Latin America deliver substantial carbon benefits alongside biodiversity, fodder, fuelwood, and income diversification. Nair et al. (2010) further noted that the carbon advantage of agroforestry derives not only from above-ground tree biomass but also from deeper rooting depths, which transfer photosynthetically fixed carbon to sub-soil layers where decomposition is slow and turnover times exceed several decades.

3.4 Biochar amendment

Biochar—the solid residue of biomass pyrolysis under low-oxygen conditions—offers a distinctive sequestration pathway because its aromatic carbon structure resists microbial decomposition for centuries to millennia. Field and modelling studies summarised by Woolf et al. (2010) estimated a global biochar mitigation potential of 0.7–1.8 Pg CO_2-equivalent year^{-1}, equivalent to roughly 12% of current anthropogenic emissions, without compromising food security or causing land-use conflict. Biochar application also tends to improve cation exchange capacity, water-holding capacity, and nutrient retention in degraded soils, though effects on crop yield vary with feedstock, pyrolysis temperature, and soil context.

3.5 Improved grazing and grassland management

Grasslands occupy approximately 25% of the ice-free terrestrial surface and hold around 343 Pg of SOC in the top one metre (FAO, 2022). Improved practices—including rotational grazing, adjustment of stocking densities, sowing of deep-rooted forage species, and silvopastoral integration—can sequester 0.10–0.80 Mg C ha^{-1} year^{-1} (Conant et al., 2017). Because grasslands often occur on marginal lands unsuited to cropping, they offer politically and economically tractable mitigation opportunities, especially in dryland regions of Asia, Africa, and South America.

3.6 Organic amendments and integrated nutrient management

Application of farmyard manure, compost, green manure, and recycled urban organic waste contributes both nutrients and stabilised carbon to soils. Maillard and Angers (2014) reported, in a global meta-analysis, that manure addition increased SOC stocks by an average of 0.20–0.70 Mg C ha^{-1} year^{-1} relative to mineral-fertilised controls. When combined with conservation tillage and cover crops within climate-smart agriculture frameworks, integrated nutrient management consistently outperforms single-practice interventions (FAO, 2019).

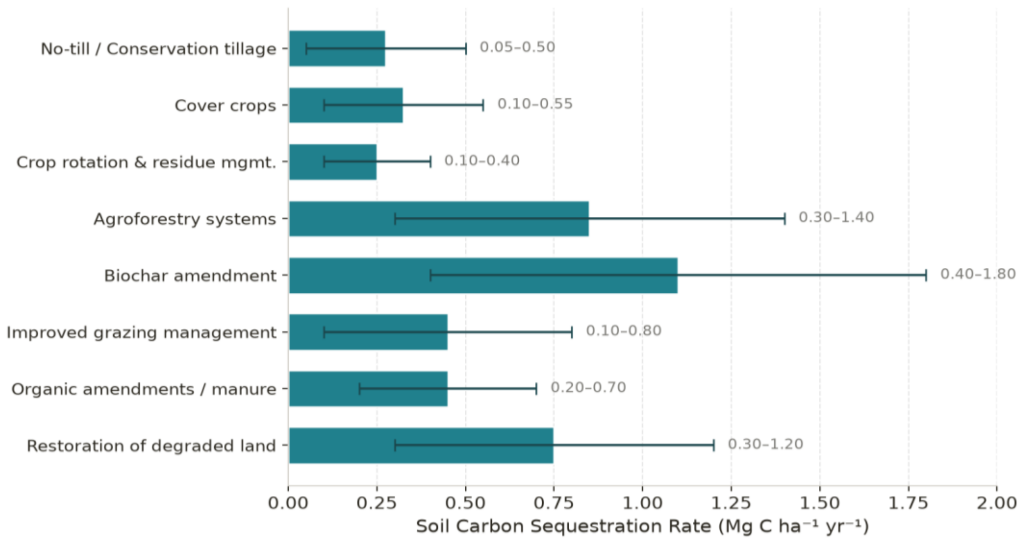


Figure3. Reported soil-carbon sequestration potential for major agricultural management practices (range, mean shown as bar)

4. Regional Patterns and Global Mitigation Potential

The distribution of carbon sequestration potential is uneven, reflecting differences in current SOC depletion, climate, land area, and management intensity. North America, Eurasia, and Europe collectively hold more than half of global cropland SOC stocks, while developing regions—particularly Sub-Saharan Africa and South Asia—contain large areas of degraded soils where restorative practices can yield disproportionately high relative gains (Zomer et al., 2017). The Food and Agriculture Organization estimated that approximately 89% of the technical mitigation potential of agriculture in developing countries lies in soil carbon sequestration (Smith et al., 2008).

Smith et al. (2008) projected a global agricultural mitigation potential of 5.5–6.0 Gt CO_2-equivalent year^{-1} at carbon prices below USD 100 per tonne, of which cropland management and grazing-land management contribute the largest shares. Subsequent assessments by Griscom et al. (2017) reaffirmed that "natural climate solutions"—including agricultural soil practices, reforestation, and wetland restoration—could supply over one-third of the cost-effective mitigation required to keep global warming below 2 °C. Figure 4 illustrates indicative regional cropland sequestration potentials based on these assessments.

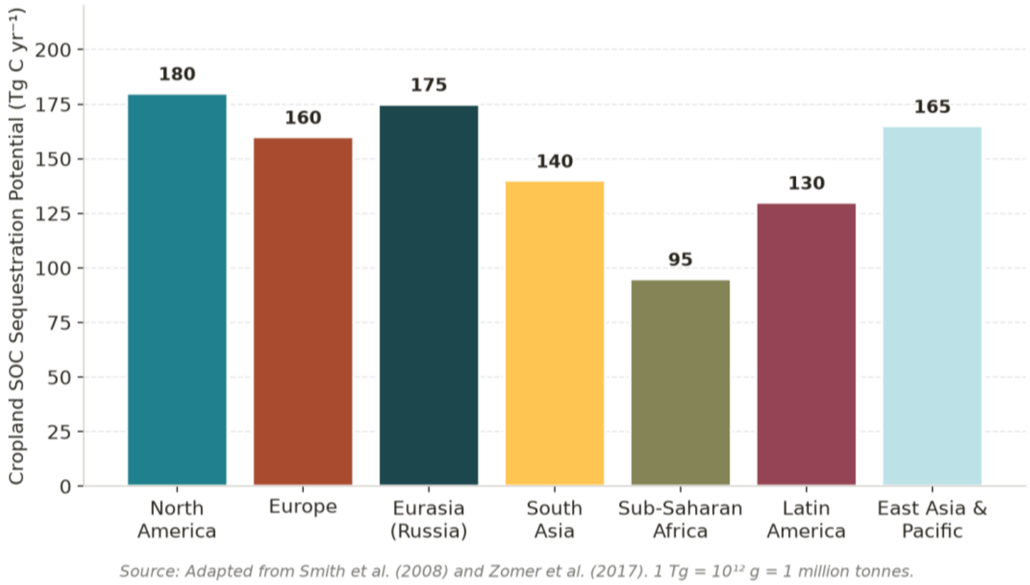


Figure4. Estimated regional cropland soil-carbon sequestration potential (Tg C year^{-1}).

5. Challenges, Trade-offs, and Monitoring

Despite the substantial biophysical potential, several constraints temper field-scale outcomes. First, sequestered carbon is impermanent: gains accumulated over decades can be reversed within a few years of resumed tillage, drought, or land-use change. Smith (2016) emphasised that sequestration is a "saturating" process, in which soils approach a new equilibrium within 20–50 years, beyond which further inputs yield little additional storage. Second, accurate measurement, reporting, and verification (MRV) of SOC change remain technically challenging because of high spatial variability and small annual signal-to-noise ratios. Innovations in remote sensing, near-infrared spectroscopy, and modelling (e.g., the FAO Global Soil Organic Carbon Map released in 2018) have improved baseline estimation, but field calibration remains essential (FAO, 2018).

Third, sequestration practices interact with other greenhouse gases. Increased nitrogen inputs to stimulate biomass and SOC may elevate nitrous oxide (N_2O) emissions, partially offsetting CO_2 removal. Cover crops, biochar, and improved grazing can in some contexts reduce these trade-offs, but careful, system-level life-cycle accounting is required (Paustian et al., 2016). Fourth, adoption depends on economic incentives, secure land tenure, technical extension, and equitable access to inputs—dimensions that vary dramatically among smallholder and commercial systems.

A further methodological concern relates to baseline selection and sampling depth. Many early studies measured SOC only in the surface 0–20 cm, where management effects are most pronounced, and consequently overstated total profile gains. Powlson et al. (2014) and Ogle et al. (2019) recommended sampling to at least 60 cm and using equivalent-soil-mass calculations to correct for differences in bulk density between treatments. These refinements have led to more conservative but more defensible estimates of sequestration potential, which are essential for credible carbon accounting in regulatory and voluntary markets.

Finally, the social dimensions of carbon sequestration deserve explicit attention. Smallholder farmers in Asia, Africa, and Latin America manage a substantial fraction of the world's cropland but often face the highest transaction costs in accessing carbon-payment schemes (Smith et al., 2008). Up-front investment in cover-crop seed, biochar production units, or agroforestry establishment can be prohibitive without targeted subsidies or community financing. Gender-disaggregated analyses further suggest that women farmers, who frequently lack secure land tenure, are systematically under-represented among beneficiaries of mitigation programmes, an inequity that policy design must redress.

6. Policy Levers and Sustainable Farming Frameworks

Effective deployment of agricultural carbon sequestration requires policy frameworks that align farmer incentives, monitoring infrastructure, and broader sustainable-development goals. Carbon-credit markets and payment-for-ecosystem-services schemes—such as the United States Department of Agriculture Climate-Smart Commodities programme launched in 2022 and the European Union Carbon Removal Certification Framework proposal—aim to translate biophysical potential into financial reward (European Commission, 2022). Certification standards (e.g., Verra VM0042 for improved agricultural land management) provide protocols for additionality, permanence, and leakage assessment, although critics argue that integrity safeguards must be strengthened to prevent over-crediting.

Integration with food-security and biodiversity objectives is equally important. The concept of climate-smart agriculture, as elaborated by the FAO (2019), explicitly seeks the triple win of productivity, adaptation, and mitigation. Embedding carbon sequestration within such frameworks—rather than treating it as an isolated objective—improves social legitimacy and reduces the risk of unintended trade-offs with food production, water resources, or rural livelihoods. National implementation will benefit from soil-health observatories, farmer-led innovation networks, and inclusive extension services. India’s National Mission for Sustainable Agriculture and the European Union’s Soil Strategy for 2030 illustrate complementary regional approaches that combine soil-carbon objectives with broader sustainability mandates (IPCC, 2022).

CONCLUSION

Carbon sequestration in agricultural systems is a scientifically credible, near-term, and multi-functional pathway for climate change mitigation. Evidence accumulated up to 2022 indicates that practices such as conservation tillage, cover cropping, agroforestry, biochar amendment, improved grazing, and organic amendments can collectively sequester roughly 1–2 Pg C $year^{-1}$ globally—an amount equivalent to a meaningful share of current anthropogenic emissions. The biophysical potential is concentrated in soils that have lost the most carbon, creating a fortunate alignment between mitigation, food security, and soil-health objectives.

However, technical potential is not realised potential. Permanence risks, measurement uncertainties, and the slow accumulation of sequestered carbon demand robust monitoring, rigorous accounting standards, and policy continuity across decades. Trade-offs with nitrous oxide emissions, water use, and yield must be evaluated at the system level. Equitable financing mechanisms and effective extension services are essential if smallholders—who manage a large share of the world's croplands and degraded soils—are to participate in carbon markets.

A balanced research and policy agenda should therefore (i) refine site-specific sequestration estimates with improved MRV technologies, (ii) integrate carbon objectives within climate-smart agriculture frameworks, (iii) develop credible incentive schemes that ensure additionality and permanence, and (iv) foster farmer participation through capacity-building and secure land tenure. With sustained investment, agricultural soils can deliver durable, low-cost, and socially beneficial contributions to climate change mitigation while underpinning the long-term sustainability of farming systems.

Acknowledgements:
The authors would like to thank all co-authors for their valuable input and timely contributions.

Funding:
This research did not receive any specific grant.

Conflict of Interest:
The authors report no conflicts of interest.

Author Contributions:
All authors participated in drafting, revising, and approving the manuscript.

REFERENCES

Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, *27*(2), 662–668.

European Commission. (2022). *Proposal for a regulation establishing a Union certification framework for carbon removals*. Brussels: European Commission.

Food and Agriculture Organization. (2018). *Global Soil Organic Carbon Map (GSOCmap) Version 1.5: Technical report*. Rome: FAO.

Food and Agriculture Organization. (2019). *Climate-smart agriculture sourcebook (2nd ed.)*. Rome: FAO.

Food and Agriculture Organization. (2022). *Global assessment of soil carbon in grasslands*. Rome: FAO.

Food and Agriculture Organization, & Intergovernmental Technical Panel on Soils. (2015). *Status of the world's soil resources: Main report*. Rome: FAO and ITPS.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., & Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences, 114*(44), 11645–11650.

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report*. Cambridge University Press.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*(5677), 1623–1627.

Maillard, É., & Angers, D. A. (2014). Animal manure application and soil organic carbon stocks: A meta-analysis. *Global Change Biology, 20*(2), 666–679.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., & Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma, 292*, 59–86.

Nair, P. K. R., Nair, V. D., Kumar, B. M., & Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy*, *108*, 237–307.

Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., & Vazquez-Amabile, G. (2019). Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports*, *9*(1), 11665.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57.

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

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, *4*(8), 678–683.

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*, *114*(36), 9575–9580.

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*(3), 1315–1324.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813.

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal*, *66*(6), 1930–1946.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56.

Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports*, *7*(1), 15554.

Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., & Wang, M. (2016). Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, *6*, 29987.