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From Soil Degradation to Soil Regeneration: A Global Review of Sustainable Practices

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Abstract:

Soil degradation impacts more than 33% of global land, challenging food security, biodiversity, climate regulation, and ecosystem services. This study compiles global research on the shift from degradation—caused by erosion, nutrient depletion, compaction, salinization, and intensive practices—to regeneration via sustainable and regenerative agriculture. Conservation tillage, cover cropping, crop rotation, organic amendments, decreased synthetic inputs, agroforestry, and integrated livestock management are among the most important methods. These treatments improve soil organic carbon (SOC), microbial diversity, water retention, and resilience. Meta-analyses and case studies conducted across continents demonstrate that yield stability or gains are associated with environmental co-benefits, but adoption hurdles (economic, knowledge, and policy) persist. The study emphasizes alignment with the UN SDGs (particularly 2, 13, and 15) and advocates for expanded implementation, long-term monitoring, and policy support to achieve land degradation neutrality by 2030.

Keywords: Soil Health, Regenerative Agriculture, Sustainable Practices, Land Degradation Neutrality, climate mitigation.

1. Introduction

Soil is a scarce resource, and regeneration rates are orders of magnitude slower than current deterioration (Amundson et al., 2015). Globally, ~24 billion tons of rich topsoil are lost annually due to erosion and mismanagement. If current trends continue, land degradation is projected to exceed 90% by 2050 (UNCCD, 2017, as noted in recent studies). Degradation processes such as water/wind erosion, salinization, acidification, compaction, nutrient mining, and organic matter loss impair agricultural productivity, biodiversity, and carbon storage, aggravating climate change and food insecurity (Shokri et al., 2025). On evolutionary timescales, soil is a non-renewable resource, with formation rates ranging from 0.01 to 1 mm per century, contrasted to erosion losses that can be 10-100 times greater under poor management. According to recent estimations, 33-52% of global land is deteriorated to some extent, with forecasts indicating that up to 95% of Earth's land would be damaged by 2050 if no action is taken. Annual topsoil loss is estimated at 24-75 billion tons, resulting in economic losses of hundreds of billions of dollars due to diminished productivity and ecosystem services. Degradation worsens climate change by releasing stored carbon (agricultural soils have lost around 133 Pg SOC since farming began) and decreasing susceptibility to droughts, floods, and nutrient deficits (Lal, 2020).

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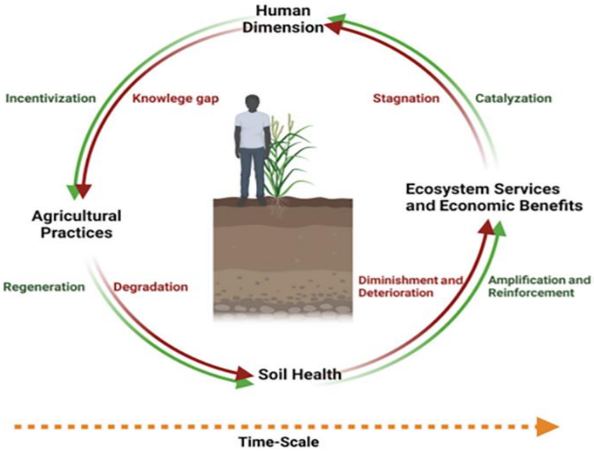

Figure1. Soil Health Cycle (adopted by Maharjan et al., 2024)

This figure 1 depicts a closed-loop soil health cycle, emphasizing the movement from degradation (e.g., erosion, low SOC) to regeneration via methods such as cover cropping and reduced disturbance, hence generating virtuous feedback for ecosystem recovery.

Regenerative agriculture has arisen as a proactive paradigm that moves beyond "sustainability" (maintaining the status quo) to active repair (Newton et al., 2020; Khangura et al., 2023). The core concepts include limiting disturbance, maximizing live roots/cover, boosting variety, integrating animals, and lowering synthetics (Regeneration International 2017). This review looks at worldwide evidence of these strategies reversing deterioration, focusing on meta-analyses, regional syntheses, and field research (2020-2025).

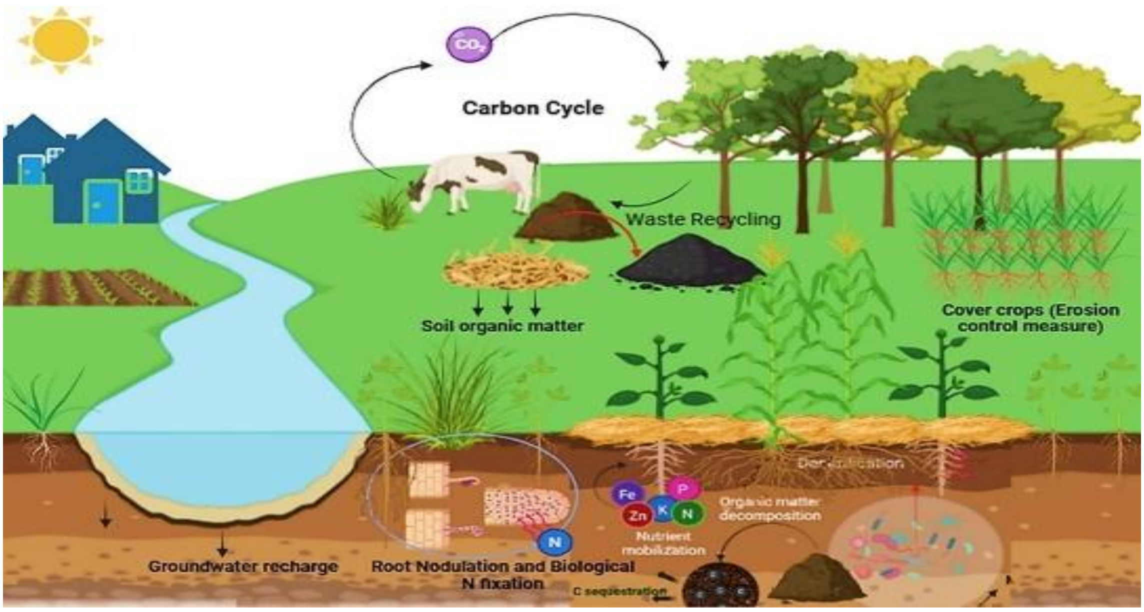

Figure 2. Regenerative pathways in rural ecosystems (Adopted by Das et al., 2025)

Figure 2, graphical representation of regenerative pathways in rural ecosystems, with arrows representing feedback from practices (cover crops and no-till) to soil repair.

2. Global Extent and Drivers of Soil Degradation:

Global degradation affects approximately 2 billion hectares, primarily in Asia and Africa (Shokri et al., 2025)

Major drivers include:

Intensive tillage and monoculture lead to erosion and loss of SOC.

Excessive use of synthetic fertilizers and pesticides leads to acidification and reduced biodiversity.

Deforestation and overgrazing lead to soil compaction and nutrient export. Climate change exacerbates these problems through extremes (droughts and floods) (IPCC-linked reports; Kopittke et al., 2025).

Degradation affects about 2-5.1 billion hectares, with substantial consequences in drylands (Africa, Asia) and highly farmed regions (Europe, North America). Water/wind erosion affects 1,100-1,500 million hectares, whereas salinization affects 300-400 million ha. Nutrient depletion is prevalent on around 33% of croplands. Recent revisions indicate that climate change will accelerate trends.

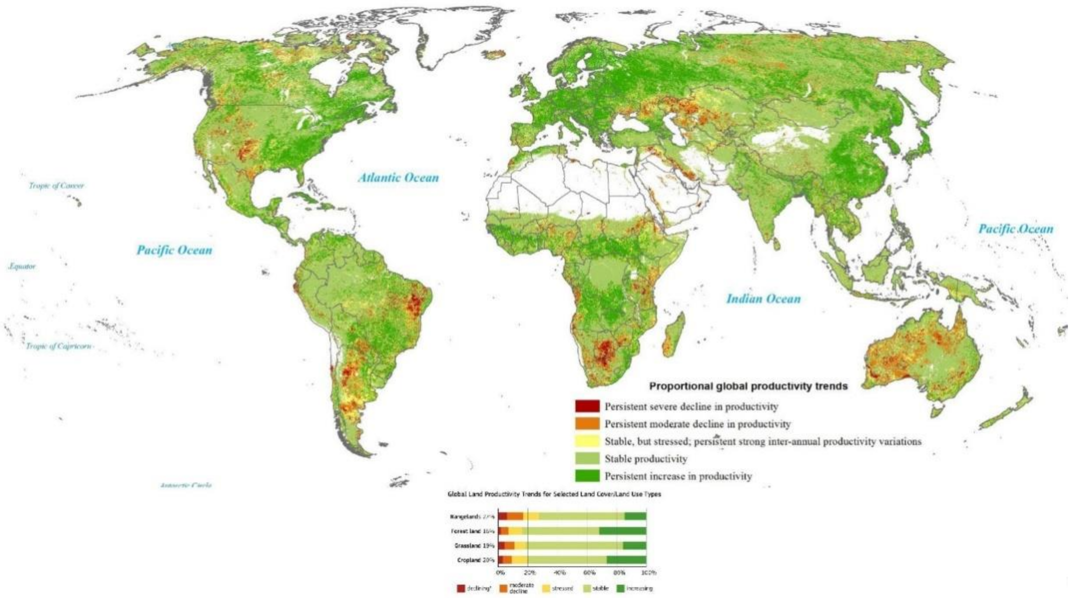

Figure 3, Land Degradation (IPCC, 2019)

Table 1. Major Soil Degradation Processes and Global Extent

Process	**Primary Cause(s)**	**Global Affected Area (million ha)**	**Key Impacts**	**References**
Water/wind erosion	Tillage, bare soil, overgrazing	1,100–1,500	Topsoil loss, reduced fertility, sedimentation	Borrelli et al., 2021; UNCCD, 2017
Salinization	Poor irrigation, sea-level rise	300–400	Osmotic stress, yield declines	Shokri et al., 2025

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Nutrient depletion	Monoculture, export without return	~33% croplands	Lower productivity, increased GHG emissions	Lal, 2020
Compaction	Heavy machinery	Widespread in mechanized areas	Reduced infiltration, root restriction	UNCCD, 2017
Organic matter loss	Intensive practices	20–30% decline in many soils	Reduced water/carbon storage, biodiversity loss	Khangura et al., 2023; Patil et al., 2025

3. Pathways to Soil Regeneration: Key Sustainable Practices

Soil health restoration is being more acknowledged as an important method for mitigating climate change and ensuring sustainable food production. Conventional agricultural techniques, which include intense tillage and synthetic inputs, have resulted in the loss of up to 50-70% of the original SOC pool in many soils (Lal, 2020). Regenerative pathways aim to counteract this tendency by focusing on the soil's biological environment.

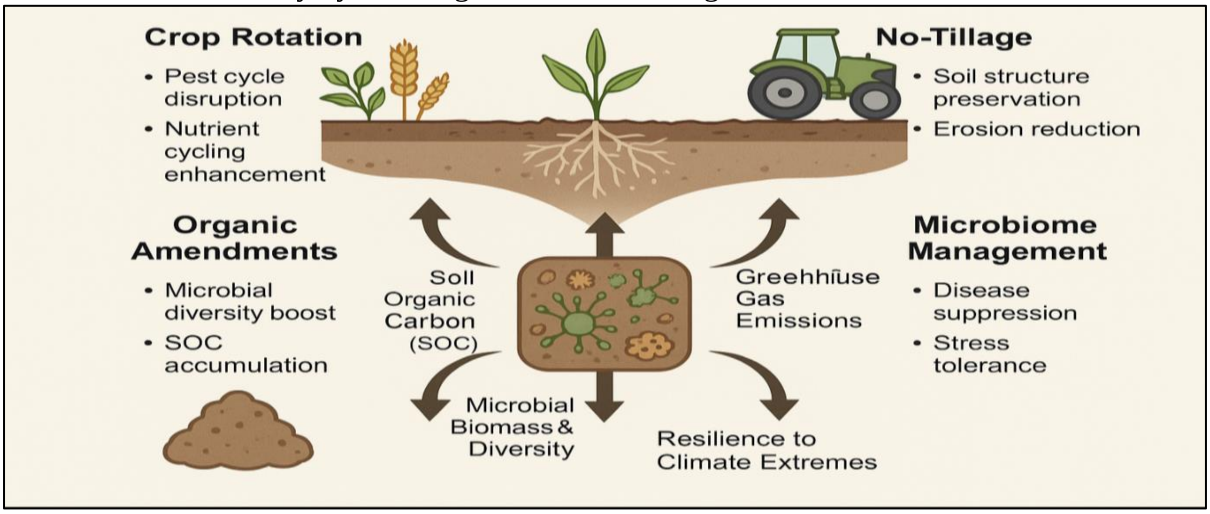

Figure 4, Integrated Management Practices Foster Soil Health, Productivity, and Ecosystem Resilience (Adopted by Liang et al., 2025)

The integrated management cycle demonstrates how activities promote soil health, production, and storage of carbon through reinforcing loops.

3.1 Minimizing Soil Disturbance (No-Till/Reduced Tillage):

Mechanical tillage disturbs the soil's structural integrity, causing aggregates to break down and organic matter to oxidize more quickly. Land managers who use no-till or reduced-tillage systems retain soil pore space and safeguard symbiotic fungus networks (mycorrhizae), which are necessary for nutrient absorption. These systems increase macrofauna activity, including earthworm populations, resulting in projected SOC benefits of 0.3 to 1.0 t/ha/yr (Lal, 2020; Montgomery, 2017).

3.2 Increasing Biodiversity (Crop Rotation and Diversification):

The transition from monocultures to complex polycultures and diverse crop rotations disrupts disease and insect life cycles, minimizing the need for chemical intervention.

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Diversified systems use distinct root designs to obtain nutrients at different soil depths, increasing total nutrient efficiency. According to meta-analyses, increasing plant variety can result in SOC benefits ranging from 0.2 to 0.8 t/ha/year by offering a wider range of organic inputs (Lal, 2020; Paustian et al., 2016).

3.3 Organic Amendments (Compost, Manure, and Biochar):

The judicious use of organic amendments accelerates the regeneration of deteriorated soils. While farmyard manure (FYM) and compost give rapid nitrogen and microbial inoculation, biochar serves as a long-term carbon sink. Biochar's porous structure allows for long-term carbon storage and pollutant remediation, with sequestration rates ranging from 0.5 to 2.0 t/ha/year (Lehmann and Joseph, 2015; Rhodes, 2017).

3.4 Integrating Livestock and Agro forestry:

Integrated systems replicate the complexity of natural ecosystems. Managed rotational grazing (or "mob grazing") involves high-density, short-duration grazing to stimulate plant growth and cycle nutrients through manure. In addition, agroforestry incorporates perennial woody vegetation, which offers deep-root stability and long-term woody biomass storage. These methods have a synergistic impact, increasing the soil's water infiltration and storage capacity.

3.5 Evidence from Global Case Studies and Meta-Analyses:

Meta-analyses consistently show that regenerative techniques improve SOC, with rates changing according to integration level, climate, and duration. Temperate systems frequently demonstrate improvements without yield penalties, whereas tropical/subtropical locations have larger relative gains but greater unpredictability due to rapid decomposition and erosion concerns. Long-term (>10-20 year) deployment has the greatest impact, since POC (particulate organic carbon) accumulates initially and MAOC (mineral-associated organic carbon) stabilizes with time.

Table 2: Comparative Impacts from Recent Meta-Analyses

Practice	SOC Change (t/ha/yr or % increase)	Yield Impact	Other Benefits	Key Sources
No-till + cover crops	+0.3 to +1.0 t/ha/yr	Neutral to +10% (long-term)	↑ microbes, ↓ erosion, improved resilience	Khangura et al. 2023; Patil et al., 2025
Biochar application	+0.5 to +2.0 t/ha/yr; up to +37.7% in some systems	+11–19% (often in acidic soils)	Remediation, drought resistance, ↓ GHG	Ye et al., 2020
Diversified rotations	+0.2 to +0.8 t/ha/yr	Stable to + (yield stability ↑)	Pest control, biodiversity, nutrient cycling	Various 2023–2025 meta-analyses
Organic amendments (e.g., FYM, compost)	Highest gains (e.g., +6–13% in long-term)	Variable to +	Nutrient cycling, microbial recovery	Patil et al., 2025
Integrated systems (multiple practices)	+0.4 to +1.5 t/ha/yr	Often stable/+ long-term	Resilience, balanced POC/MAOC, ↓ GWP	Villat and Nicholas, 2024

4 Regional Evidence:

Regional results are influenced by the local climate, soil type, and socioeconomic background. Practices are particularly successful in areas with significant deterioration and big yield gaps.

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4.1 India

A meta-analysis of 147 research spanning agro-ecological zones reveals that farmyard manure (FYM), green manure, and compost provide the maximum SOC improvements (e.g., effect sizes of 6.48-6.56 in 20-40 year studies). Integrated nutrient management and crop diversification improve microbial biomass and long-term stability, especially in tropical and subtropical soils with low baseline SOC. Long-duration tests (>20 years) demonstrate the highest regeneration, which is consistent with India's various climates and heavy cropping pressures (Patil et al., 2025).

4.2 Australia/Southeast Asia

In drylands (semi-arid Mediterranean climates), no-till coupled with residue retention and cover crops efficiently increases soil organic carbon and water-holding capacity, which is crucial in drought-prone regions. Studies in Western Australia have found site-specific improvements in coarse-textured soils, such as reduced wind erosion and improved microbial function under conservation tillage. These approaches promote yield stability in low-rainfall areas, while initial transitions must be carefully managed to minimize short-term declines (Khangura et al., 2023).

4.3 Europe/North America

Biochar mixed with decreased tillage improves yield stability and SOC sequestration, particularly in temperate soils prone to compaction and acidity. According to meta-analyses, biochar increases yields by 11-19% in nutrient-poor or polluted soils, with additional advantages such as heavy metal cleanup and enhanced water retention. Long-term studies show neutral to positive yield responses with no significant GHG trade-offs, enabling implementation in automated systems (Ye et al., 2020; Villat and Nicholas, 2024).

4.4 Africa/South America

Agroforestry and rotational (holistic) grazing are effective erosion control and regeneration strategies in drylands and savannas. In Sub-Saharan Africa, agroforestry is expected to minimize soil loss by up to 30% by 2040, while rotational grazing enhances rangeland health, fodder quality, and animal output by allowing for recovery periods. Silvopastoral systems in South America improve biodiversity and nutrient cycling, with high potential in degraded pastures. Success is dependent on community involvement and context-specific design (e.g., Zambia/Tanzania examples; Abegunde et al., 2020).

5. Yield and Co-Benefits:

Many long-term research (>10 years) reveal that regenerative systems produce neutral or positive yields with improved stability under extremes (e.g., droughts). Meta-analyses suggest that initial drops are probable, but that recovery will be achieved through better resilience, nutrient efficiency, and biodiversity. Co-benefits such as decreased erosion, increased microbial diversity, and improved water/nutrient retention outweigh short-term trade-offs in varied systems.

5.1 Co-Benefits and Alignment with Global Goals:

Regenerative methods have the ability to trap carbon on a global scale, with estimates for improved agricultural management ranging from 0.4 to 1.0 Gt C/yr (in line with "4 per 1000" and contemporary forecasts). This contributes to climate mitigation (negative emissions equivalent to a fforestation at ~160 USD/t CO_2e by 2050, primarily in the Global South). Co-benefits include increased biodiversity (microbial and above-ground variety), better water security (infiltration/retention), nutrient cycle efficiency, and reduced erosion/salinization. These are closely aligned with the UN SDGs: SDG 2 (zero hunger via resilient yields), SDG

13 (climate action through sequestration and GHG reduction), SDG 15 (life on land via ecosystem restoration), and LDN aims by reversing degradation and improving soil health.

6. Barriers, Gaps, and Recommendations:

6.1 Adoption Barriers

Economic barriers include transition expenses (e.g., no-till equipment, first modifications) and short-term yield hazards. Knowledge gaps among farmer's/extension services, policy misalignment (subsidies favoring synthetics), and scale difficulties (labor for varied systems) all hinder acceptance, especially in resource-constrained areas.

6.2 Research Gaps

Long-term (>10-20 year) research are limited, particularly in tropical/subtropical zones with high decomposition rates and significant degrading pressures. Quantifying complete life-cycle GHG trade-offs (e.g., N_2O emissions from legume cover crops or manure transport), social equity elements (e.g., gender, smallholder/indigenous access, community impacts), and integrated system effects (combining different techniques) remains a challenge. Standardized measures for SOC sequestration verification, biodiversity recovery, and economic assessment are insufficient, impeding carbon credit markets and policy scaling. Perennial systems, rangelands, and climate extreme resilience in various agroecosystems are all topics that have received little research. More randomized controlled trials and participatory farmer-led research are required to bridge the process-versus-outcome divide and enhance context-specific bundles.

6.3 Recommendations

6.3.1 Financial Incentives and De-risking

Redirect subsidies from conventional inputs to regenerative transitions (e.g., repurposing some of the global ~700 billion yearly agricultural/fossil fuel subsidies). Expand programs like the USDA's 2025 Regenerative Pilot Program (700 million through EQIP/CSP for whole-farm planning, cover crops, and soil health), EU pesticide reduction objectives, and efforts like California's Healthy Soils Program and Brazil's Low Carbon Agriculture Program. Scale carbon/biodiversity credits (e.g., through blended financing, premiums for regeneratively generated items) and transition assistance (e.g., compensation for initial yield drops, low-interest loans, risk-sharing insurance). Prioritize integrated public-private methods to reduce investment risk, with a focus on small and medium-sized farms in the Global South.

6.3.2 Knowledge and Extension System

Enhance farmer-led extension through participatory monitoring, digital technologies (soil health analytics, precision agriculture), and advisory councils (e.g., the USDA's Chief's Regenerative Agriculture Advisory Council). Invest in regional training, demonstration farms, and peer networks to increase technical capacity and confidence. Increase consumer education and demand for regenerative products to generate market pull.

6.3.3 Policy and Institutional Reforms

Incorporate regenerative concepts into national policies that are consistent with UN SDGs, LDN objectives, and NDCs (e.g., through UNCCD's LDN Target Setting Programme 2.0 and synergies with NAPs/climate adaptation). Create flexible, outcome-based standards (drawing on the work of the Regenerative Organic Alliance and the Savory Institute) while avoiding unduly restrictive certification. Encourage intra-agency collaboration (e.g., USDA-NRCS) and landscape-scale methods (e.g., regenerating entire agriculture landscapes to improve supply chain resilience).

6.3.4 Research and Monitoring Priorities

Long-term, multi-site trials in underrepresented regions should be funded; SOC/biodiversity measures should be standardised; and equity-focused research should be prioritized. To establish genuine carbon markets, support worldwide platforms for data exchange and verification (such as the FAO worldwide Soil Partnership and the 4 per 1000 Initiative).

7 Conclusions

Regenerative practices—such as no-till with cover crops, diversified rotations, organic amendments, integrated livestock, and agroforestry—effectively reverse soil degradation, sequester SOC at meaningful rates (typically 0.3–2.0 t C/ha/yr, with integrated systems strongest), and improve agroecosystem resilience to climate extremes, according to solid, mounting evidence from global meta-analyses, regional syntheses, and 2020–2025 field studies. With significant co-benefits like better water retention, nutrient cycling, biodiversity recovery, decreased erosion/salinization, and alignment with global goals (UN SDGs 2, 13, 15; LDN targets; "4 per 1000" initiative), long-term implementations frequently produce neutral to positive productivity outcomes. Although sequestration potentials differ by region (higher in degraded croplands with yield gaps), realistic global estimates from improved cropland management range from 0.28 to 0.68 Gt C/yr (or up to 0.7 to 2.5 $GtCO_2e$/yr from key practices), meaningfully mitigating climate change without compromising food security when context-adapted.

Despite these benefits, economic risks, knowledge gaps, policy distortions, and structural impediments continue to impede adoption; these issues are being addressed more and more by 2025 efforts including blended financing, large-scale pilot funding, and subsidy redirection. In order to reverse degradation trends, create resilient food systems, and secure soils in the face of escalating climate pressures, governments, the private sector, and communities must prioritize de-risked incentives, farmer-centered extension, standardized monitoring, and landscape-level integration. Regenerative agriculture provides a proven, comprehensive road to land degradation neutrality, improved human and planetary health, and sustainable wealth for future generations with focused effort.

8. References:

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., & Sparks, D. L. (2015). Soil and human security in the 21st century. *Science*, 348(6235), 1261071. https://doi.org/10.1126/science.1261071

Abegunde, V. O., Sibanda, M., & Obi, A. (2020). Mainstreaming climate-smart agriculture in small-scale farming systems: a holistic nonparametric applicability assessment in South Africa. *Agriculture*, *10*(3), 52.

Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J., Ballabio, C., ... & Panagos, P. (2021). Soil erosion modelling: A global review and statistical analysis. *Science of the total environment*, *780*, 146494.

Das S, Suman Dutta, Malini Roy Choudhury, Sourav Garai, Siddhartha Mukherjee, Sudip Sengupta, Soujanya Jana, Saikat Dey, Anannya Dhar, Sayantika Dutta, Amit Awasthi, (2025). Regenerating rural soil and ecosystems: A 15-year systematic review of emerging methods and technologies, Science of The Total Environment, Volume 990, 179926, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2025.179926.

IPCC, (2019): Summary for Policymakers. In: *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* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability*, 15(3), 2338. https://doi.org/10.3390/su15032338

Kopittke, P. M., Harper, S. M., Asio, L. G., Asio, V. B., Batalon, J. T., Batuigas, A. M. T., ... & Sanchez, P. B. (2025). Soil degradation: An integrated model of the causes and drivers. *International Soil and Water Conservation Research*.

Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation, 75*(5), 123A-127A. https://doi.org/10.2489/jswc.2020.0620A

Lehmann, J., & Joseph, S. (Eds.). (2015).*Biochar for environmental management: Science, technology and implementation*. Routledge.

Liang, X., Yu, S., Ju, Y., Wang, Y., & Yin, D. (2025). Integrated Management Practices Foster Soil Health, Productivity, and Agroecosystem Resilience. Preprints. https://doi.org/10.20944/preprints202506.2355.v1

Maharjan, B., Das, S., Thapa, V. R., & Sharma Acharya, B. (2024). Soil health cycle. *Agrosystems, Geosciences & Environment, 7*, e20504. https://doi.org/10.1002/agg2.20504

Montgomery, D. R. (2017).*Growing a revolution: Bringing our soil back to life*. W. W. Norton & Company.

Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., & Johns, C. (2020). What is regenerative agriculture? A review... *Frontiers in Sustainable Food Systems*, 4, 577723.

Paustian, K., Lehmann, J., Ogle, S., et al. (2016). Climate-smart soils. *Nature, 532*(7597), 49-57. https://doi.org/10.1038/nature17174

Patil, M., Perumal, C., Choudhari, P., (2025). Differential impacts of regenerative agriculture practices on soil organic carbon: A meta-analysis of studies from India. *Scientific Reports, 15*, 33470. https://doi.org/10.1038/s41598-025-12149-6

Rhodes, C. J. (2017). The imperative for regenerative agriculture. *Science Progress, 100*(1), 80-129. https://doi.org/10.3184/003685017X14876756699229

Shokri, N., Robinson, D. A., Afshar, M., Alewell, C., Aminzadeh, M., Arthur, E., ... & Or, D. (2025). Rethinking global soil degradation: Drivers, impacts, and solutions. *Reviews of geophysics*, *63*(4), e2025RG000883.

UNCCD. (2017). Global land outlook.van der Esch, S. (2017). Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: scenarios for the UNCCD Global Land Outlook.

Villat, J., and Nicholas, K. A. (2024). Quantifying soil carbon sequestration from regenerative agricultural practices in crops and vineyards. *Frontiers in Sustainable Food Systems, 7*, 1234108. https://doi.org/10.3389/fsufs.2023.1234108

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, *36*(1), 2-18.