ENVIRONMENTAL REPORTS

Review Article
ISSN: 3041-556X
Journal homepage: https://er.researchfloor.org/

Interactive Effects of Groundwater Depletion and Climate Variability on Agricultural Carbon Sequestration

Prajval V

Department of GPS Institute of Agricultural Management, Peenya Industrial Estate, Bengaluru, Karnataka 560058, India

Citation: Prajval V (2023). Interactive Effects of Groundwater Depletion and Climate Variability on Agricultural Carbon Sequestration. *Environmental Reports; an International Journal*. **DOI: https://doi.org/10.51470/ER.2023.4.2.23**

Corresponding Author: **Prajval V** | E-Mail: **(prajvalv123@gmail.com)**

Received 28 March 2023 | Revised 25 April 2023 | Accepted 29 May 2023 | Available Online June 26 2023

ABSTRACT

Agricultural soils are among the largest terrestrial carbon reservoirs and play a critical role in mitigating climate change through carbon sequestration. However, their capacity to store carbon is increasingly threatened by the combined pressures of groundwater depletion and climate variability. Groundwater is essential for sustaining crop yields, soil organic matter inputs, and microbial processes, all of which underpin soil carbon storage. Yet, declining aquifers reduce irrigation security, disrupt nutrient cycling, and heighten vulnerability to climatic stressors. Simultaneously, climate variability—manifested through irregular precipitation, temperature extremes, droughts, and floods—alters soil moisture regimes, accelerates decomposition, and undermines carbon stabilization. Importantly, the interaction between these two drivers produces nonlinear effects: groundwater depletion amplifies the impacts of climate-induced drought, while climate variability increases irrigation demand, accelerating aquifer decline. This review synthesizes current evidence on the interactive effects of groundwater depletion and climate variability on agricultural carbon sequestration. We evaluate mechanisms, case studies, and model-based findings, highlighting how coupled water–carbon dynamics shape the resilience of agroecosystems. Finally, we discuss management strategies such as sustainable groundwater use, climate-smart agriculture, and integrated policy approaches that can safeguard both carbon storage and food security. Understanding these interdependencies is crucial for designing future agricultural systems that remain productive while making meaningful contributions to climate change mitigation.

Keywords: *water–carbon nexus, agroecosystem resilience, sustainable irrigation*

Introduction

Agriculture sits at the intersection of global challenges involving food security, environmental sustainability, and climate change. As the world population is projected to exceed 9.7 billion by 2050, the demand for food, fiber, and bioenergy continues to rise, placing unprecedented pressure on land, soil, and water resources. Meeting this demand while mitigating greenhouse gas (GHG) emissions requires transformative strategies that balance productivity with environmental stewardship. Carbon sequestration in agricultural systems—primarily through soil organic carbon (SOC) accumulation and biomass enhancement—has been increasingly recognized as a critical tool for climate change mitigation and adaptation [1]. The potential of agriculture to function as a net carbon sink is strongly influenced by hydrological dynamics, especially groundwater availability, and by broader climatic variability. The interplay between these two factors introduces complexities that are not yet fully understood but are vital for shaping sustainable management strategies.

Groundwater, which provides nearly 40% of the world's irrigation water, is the lifeline of modern agriculture. In regions such as South Asia, North China, the Middle East, and parts of North America, groundwater pumping has enabled substantial gains in agricultural productivity over the past five decades. Yet, this dependence has come at the cost of widespread groundwater depletion, declining water tables, and increasing salinity in aquifers [2]. The depletion of groundwater resources directly impacts the carbon balance of agricultural landscapes. On one hand, irrigation enables higher biomass production, greater root growth, and enhanced residue return to soils—pathways that increase SOC. On the other hand, overexploitation of groundwater reduces the long-term viability of irrigation, diminishes soil health, and can lead to land degradation, thereby undermining carbon storage potential. The decline in water availability also restricts farmers' ability to adopt carbon-sequestering practices such as cover cropping, residue retention, or agroforestry, which depend on reliable water supplies.

Climate variability adds another dimension of complexity. Changes in precipitation regimes, temperature extremes, evapotranspiration rates, and the frequency of droughts or floods can significantly influence both groundwater recharge and crop productivity. For example, prolonged droughts not only increase irrigation demand but also limit aquifer recharge, compounding the risk of depletion. Conversely, extreme rainfall events may recharge aquifers in some regions but can also cause soil erosion and nutrient leaching, reducing SOC retention. Moreover, elevated temperatures accelerate SOC mineralization, thereby offsetting gains from carbon sequestration practices. Thus, climate variability interacts with groundwater dynamics in ways that can either amplify or mitigate agriculture's carbon sequestration potential.

The importance of examining these interactions lies in their policy and management implications. Current global initiatives, such as the "4 per 1000" initiative, which advocates for increasing SOC stocks by 0.4% per year to mitigate climate change, and the Sustainable Development Goals (SDGs) underscore the need for integrated resource management. However, many carbon sequestration strategies are designed without adequately considering the water dimension.

For instance, practices like conservation tillage or biochar application are often evaluated based on their carbon outcomes alone, without accounting for their water-use efficiency or groundwater recharge potential. Similarly, irrigation policies are frequently assessed in terms of water savings, while their implications for SOC dynamics remain underexplored. A holistic understanding of the groundwater–climate–carbon nexus is therefore essential to avoid unintended trade-offs and to design interventions that maximize synergies [3]. Regional disparities further complicate the picture. In water-scarce regions such as the Indo-Gangetic Plains or the U.S. High Plains Aquifer system, groundwater depletion threatens the very foundation of irrigation-based carbon sequestration strategies. Meanwhile, in humid regions with high rainfall variability, climate extremes may be the dominant constraint. Additionally, socioeconomic and technological contexts influence how farmers adapt to water stress and climate variability, with consequences for carbon sequestration. Wealthier farmers may adopt efficient irrigation technologies like drip systems or shift to drought-resistant crop varieties, while resource-poor farmers may resort to groundwater overpumping or unsustainable land-use practices that exacerbate carbon losses. These disparities highlight the need for region-specific analyses and policies that align water management with carbon sequestration goals.

Scientific research is beginning to address these complexities through modeling approaches, remote sensing, and long-term field experiments. Crop simulation models such as DSSAT and APSIM are being coupled with groundwater models to predict how changes in irrigation and climate affect SOC dynamics. Similarly, remote sensing tools provide large-scale insights into evapotranspiration, vegetation cover, and soil moisture, which are crucial for understanding carbon–water linkages. Yet, significant gaps remain in integrating these tools into comprehensive frameworks that can inform both policy and practice. For example, while groundwater depletion rates are well-documented in many regions, their implications for long-term SOC trajectories remain poorly quantified. Likewise, the feedback effects of climate extremes on groundwater recharge and carbon storage are not fully captured in existing models [4]. This review seeks to synthesize current knowledge on the interactive effects of groundwater depletion and climate variability on agricultural carbon sequestration potential. Specifically, it aims to (i) highlight the mechanisms by which groundwater dynamics influence carbon storage in soils and crops, (ii) explore how climate variability interacts with groundwater availability to shape sequestration outcomes, (iii) assess regional disparities and case studies, and (iv) identify opportunities for integrated management strategies that align water use with carbon sequestration objectives. By bridging hydrology, agronomy, and climate science, this review underscores the need for a systems approach that moves beyond siloed perspectives. Such integration is essential for developing resilient agricultural systems that not only feed a growing population but also contribute meaningfully to global climate mitigation goals.

2. Groundwater Depletion and Agricultural Carbon Sequestration

2.1 Groundwater as a Carbon Cycle Driver

Groundwater serves as a critical driver of the terrestrial carbon cycle by sustaining crop productivity, particularly in arid and semi-arid regions where rainfall is insufficient to meet agricultural water demands. Irrigation from groundwater ensures adequate soil moisture, enabling photosynthesis, biomass accumulation, and the deposition of organic residues into the soil. This continuous input of root biomass, crop residues, and microbial byproducts forms the foundation of soil organic carbon (SOC) sequestration. Reliable groundwater supplies also allow farmers to adopt carbon-sequestering practices such as crop diversification, residue retention, and agroforestry, which all depend on stable soil water availability [5]. However, when groundwater is depleted, the carbon cycle in agricultural systems is disrupted. Reduced irrigation capacity leads to water stress, diminished plant growth, and shallow rooting systems that contribute fewer organic inputs to the soil. Long-term declines in groundwater levels can thus translate into reduced SOC stocks, diminishing the soil's role as a carbon sink. Moreover, groundwater depletion often compels shifts toward low-water-use crops, which typically generate less biomass and residue, further reducing the carbon sequestration potential of agricultural landscapes. For example, in parts of the Indo-Gangetic Plain, overpumping of aquifers has already resulted in reduced irrigation intensity, leading to lower crop yields and carbon inputs. Similar trends have been observed in the U.S. High Plains, where the decline of the Ogallala Aquifer threatens the long-term sustainability of irrigated maize and wheat systems.

2.2 Soil Organic Carbon and Groundwater Dynamics

Soil organic carbon dynamics are tightly coupled with groundwater availability. Adequate soil water not only supports plant growth but also regulates microbial activity, soil respiration, and decomposition rates. Under optimal moisture conditions, microbial efficiency enhances carbon stabilization in soil aggregates, increasing SOC persistence. In contrast, water stress from groundwater depletion has two major impacts: it reduces carbon inputs by limiting biomass production, and it accelerates SOC losses through enhanced mineralization. Dry soils tend to heat up more quickly, creating higher soil temperatures that stimulate microbial decomposition of organic matter. This paradoxical effect—less input but faster decomposition—amplifies SOC decline [6]. Regions undergoing rapid aquifer depletion provide empirical evidence of this linkage. In northern India's Indo-Gangetic Plain, declining groundwater levels have coincided with reductions in wheat and rice productivity, with direct implications for carbon sequestration. Similarly, in the U.S. High Plains, groundwater depletion has been associated not only with yield losses but also with soil degradation, as reduced irrigation leads to higher erosion risk and diminished organic matter retention. These examples highlight that groundwater depletion does not merely threaten water security; it fundamentally alters the soil carbon balance, undermining climate mitigation goals tied to agriculture.

2.3 Groundwater Quality and Carbon Fluxes

Beyond quantity, the quality of groundwater also plays a decisive role in shaping carbon fluxes in agricultural systems. Declining water tables are frequently associated with deteriorating groundwater quality, including increased salinity, higher nitrate concentrations, and elevated levels of trace elements. These changes influence soil biogeochemistry and microbial activity, with consequences for carbon cycling [7]. Saline irrigation water, for instance, reduces plant water uptake and growth, thereby lowering biomass input into soils. At the same time, soil salinization can suppress microbial activity, altering decomposition pathways and reducing SOC stability.

Elevated nitrate levels from groundwater not only pose risks of leaching into surface waters but also stimulate soil microbial processes that increase nitrous oxide emissions, a potent greenhouse gas, thereby offsetting gains from carbon sequestration. Moreover, poor-quality groundwater can exacerbate soil structural decline, leading to compaction or sodicity, which further restricts root growth and organic matter accumulation.

In coastal agricultural regions, groundwater depletion often induces seawater intrusion, introducing high salt concentrations into irrigation supplies. This phenomenon has been documented in parts of South Asia, the Mediterranean, and California, where salinization reduces crop yields and weakens carbon sequestration capacity. Thus, groundwater depletion not only reduces the volume of water available for irrigation but also degrades its quality, creating a dual challenge for maintaining agricultural productivity and soil carbon stocks.

Table 1. Mechanisms linking groundwater depletion and carbon sequestration in agriculture

Mechanism	Impact on Soil/Plant System	Effect on Carbon Sequestration	Example Regions
Reduced irrigation capacity	Limited soil moisture, shallow rooting	Decreased SOC inputs due to lower biomass	Indo-Gangetic Plain (India), High Plains (USA)
Water stress & soil temperature rise	Accelerated organic matter decomposition	Increased CO_2 emissions from soils	Mediterranean cropping systems
Decline in water quality (salinity, nitrate leaching)	Altered microbial processes, reduced nutrient availability	Lower microbial carbon use efficiency, higher respiration	Coastal aquifers, North China Plain
Energy-intensive groundwater pumping	Higher GHG emissions from energy use	Indirect negative effect on the agricultural carbon balance	South Asia, Middle East

Table 2. Climate variability impacts on agricultural carbon sequestration

Climate Stressor	Agricultural Effect	Carbon Cycle Response	References (Placeholder)
Drought	Reduced crop yields, lower biomass	Decline in SOC accumulation	[1]
Heat waves	Increased soil respiration, plant stress	Higher CO_2 emissions, SOC loss	[2]
Erratic rainfall	Waterlogging, anaerobic soils	Methane (CH_4) emissions from flooded soils	[3]
Changing precipitation seasonality	Crop calendar disruptions	Altered carbon input-output balance	[4]

Table 3. Potential management interventions for sustaining carbon sequestration under groundwater and climate stress

Intervention	Mechanism	Benefits for Carbon Sequestration	Co-benefits
Deficit irrigation / drip irrigation	Reduces water loss, maintains productivity	Sustains biomass input to soils	Improves water-use efficiency
Biochar application	Enhances soil water retention, stable carbon pool	Increases SOC stability	Mitigates drought stress
Agroforestry systems	Deep roots tap subsoil water, and continuous litter input	Long-term carbon accumulation	Enhances biodiversity, reduces evapotranspiration
Managed Aquifer Recharge (MAR)	Restores groundwater levels	Stabilizes irrigation for crops	Reduces land subsidence, improves water quality
Renewable-powered irrigation (solar pumps)	Cuts energy-related CO_2 emissions	Indirectly reduces carbon footprint	Links energy, water, and carbon nexus

3. Climate Variability and Agricultural Carbon Sequestration

3.1 Climate Drivers of Carbon Cycling

Climate variability, encompassing fluctuations in temperature, precipitation, and extreme weather events, is a critical determinant of agricultural carbon sequestration. Temperature controls plant physiological processes, microbial activity, and decomposition rates, while rainfall regulates soil moisture availability and nutrient cycling. Variability in these factors alters the balance between carbon inputs through plant biomass and outputs via soil respiration. For instance, elevated temperatures may increase crop growth in cooler regions but often accelerate microbial decomposition of soil organic matter, resulting in net carbon loss [8]. Similarly, irregular rainfall patterns—particularly droughts and intense rainfall events—disrupt soil moisture dynamics and reduce the stability of soil organic carbon (SOC).

3.2 Temperature Extremes and Soil Processes

Extreme heat events have become more frequent with climate change, exerting profound effects on both crop growth and SOC dynamics. Heat stress reduces crop yields by impairing photosynthesis and increasing evapotranspiration rates, which diminishes the amount of organic matter returned to the soil. At the microbial scale, higher soil temperatures accelerate enzymatic activity, enhancing decomposition of existing SOC [9]. This "carbon pulse" effect can lead to significant short-term carbon losses during heatwaves, especially in soils with already low organic matter. Conversely, cold spells may slow microbial activity but also reduce plant productivity, underscoring the complexity of temperature-driven carbon cycling.

3.3 Precipitation Variability and Soil Carbon Stability

Changes in rainfall patterns exert some of the strongest impacts on SOC sequestration. Prolonged droughts reduce soil moisture, limiting plant growth and carbon input. Additionally, dry soils are more susceptible to erosion, causing loss of SOC-rich topsoil. When drought is followed by sudden intense rainfall, the problem is compounded: soils experience runoff, leaching, and microbial "flushes" that release large amounts of carbon dioxide. In contrast, excessive rainfall or waterlogging restricts oxygen availability in soils, leading to anaerobic conditions that slow decomposition but increase methane emissions [10]. Thus, climate-driven precipitation extremes can simultaneously undermine SOC stability and increase greenhouse gas emissions.

3.4 Extreme Events and Long-Term Carbon Balance

Beyond gradual climate variability, extreme events such as floods, cyclones, and prolonged droughts impose acute disturbances on soil carbon processes. Flooding can erode topsoil layers rich in organic carbon, while storms may damage perennial vegetation that contributes to long-term carbon storage. Repeated exposure to extreme events reduces soil resilience and carbon sequestration potential over time. Agricultural systems in regions such as Sub-Saharan Africa and

South Asia, already characterized by marginal soils and water scarcity, are particularly vulnerable [11]. These climate-driven challenges highlight the urgent need to integrate adaptive land management strategies—such as conservation tillage, mulching, and agroforestry—that buffer soils against carbon losses during climate extremes.

4. Interactive Effects of Groundwater Depletion and Climate Variability

4.1 Synergistic Stresses on Agricultural Systems

Groundwater depletion and climate variability rarely act in isolation; instead, they interact synergistically to influence agricultural carbon sequestration. Depleted aquifers reduce the capacity of farmers to buffer against rainfall variability, leaving crops more vulnerable to drought. Similarly, rising temperatures and changing precipitation patterns accelerate groundwater withdrawals, exacerbating depletion. Together, these stressors diminish the stability of soil organic carbon (SOC) by simultaneously reducing biomass inputs and increasing decomposition losses [12]. The combined effect is often nonlinear, with greater carbon losses than would be expected from either stressor alone.

4.2 Crop Productivity and Carbon Inputs

Climate variability intensifies the consequences of groundwater depletion by restricting irrigation opportunities during droughts. When groundwater is scarce, crops cannot meet evapotranspiration demands, leading to reduced yields and lower residue inputs to soils. In regions such as the Indo-Gangetic Plain and U.S. High Plains, studies have shown that climate-induced droughts accelerate aquifer decline, creating a feedback loop of reduced crop productivity and diminished carbon sequestration potential [13]. Moreover, farmers often shift to stress-tolerant, low-yield crops under these conditions, further lowering carbon input to soils.

4.3 Soil Carbon Losses Under Combined Stress

The interactive stress of low water availability and high temperatures creates ideal conditions for rapid soil organic matter decomposition. As soils dry out, microbial communities become less efficient in stabilizing carbon. When rewetting occurs after drought, microbial respiration spikes, releasing large amounts of CO_2. These “wet-dry cycles,” intensified by climate variability, are particularly destructive in water-limited systems with depleted groundwater reserves. Additionally, aquifer depletion can lead to salinity buildup, which, combined with heat stress, reduces root growth and accelerates SOC decline. Thus, climate variability and groundwater depletion coalesce to undermine both the quantity and quality of SOC pools [14].

4.4 Implications for Climate Mitigation and Adaptation

The interactive impacts of groundwater depletion and climate variability on carbon sequestration have significant implications for climate mitigation and adaptation strategies. Soils with diminished carbon stocks not only release more CO_2 but also lose structural integrity, reducing agricultural resilience to future shocks. Managing these interactions requires integrated strategies that address both water and carbon dynamics. Approaches such as deficit irrigation, crop diversification, reduced tillage, and soil amendment with biochar can enhance SOC while conserving water. Policymakers must also consider groundwater governance frameworks that prevent overextraction while promoting climate-resilient agricultural practices. Without coordinated efforts, the dual pressures of groundwater depletion and climate variability may severely limit agriculture's role in carbon sequestration and climate change mitigation [15].

5. Management and Policy Interventions

5.1 Sustainable Groundwater Management

One of the most pressing challenges in sustaining agricultural carbon sequestration is the unsustainable extraction of groundwater. Overexploitation reduces soil moisture availability and undermines soil carbon stability. Policy interventions must therefore focus on regulating groundwater withdrawal through volumetric pricing, water quotas, or community-based allocation systems. Incentives for farmers adopting water-saving irrigation methods—such as drip or sprinkler systems—can reduce dependency on declining aquifers. Importantly, groundwater governance should be localized, acknowledging heterogeneity in aquifer recharge rates and regional hydrological conditions.

5.2 Irrigation Efficiency and Soil Health

Improving irrigation efficiency is central to mitigating the combined stress of groundwater depletion and climate variability. Practices like deficit irrigation, alternate wetting and drying (AWD) in rice, and regulated deficit irrigation in orchards have demonstrated benefits in maintaining yields while conserving water. When coupled with soil carbon-enhancing practices (mulching, cover cropping, reduced tillage), these approaches optimize water use while building soil organic matter. Enhancing soil water retention capacity through organic amendments and biochar also improves resilience to both drought and irregular rainfall events [16].

5.3 Agroecological and Nature-Based Solutions

Agroecological approaches such as crop diversification, agroforestry, and conservation agriculture simultaneously improve soil carbon storage and buffer against climate shocks. Agroforestry, for instance, increases belowground carbon inputs, enhances soil structure, and reduces evapotranspiration by providing shade. Wetland restoration and managed aquifer recharge represent nature-based solutions that not only replenish groundwater but also create carbon sinks. Policymakers should support such practices through subsidies, extension programs, and carbon credit schemes that reward farmers for carbon sequestration benefits [12].

5.4 Policy Integration: Water–Energy–Carbon Nexus

Effective management requires acknowledging the nexus between water, energy, and carbon cycles. For example, energy-intensive groundwater pumping contributes indirectly to carbon emissions, while water stress reduces carbon sequestration potential. Integrated policies that link renewable energy adoption (e.g., solar-powered irrigation pumps) with water-use efficiency can simultaneously address groundwater depletion and greenhouse gas mitigation. International frameworks such as the Paris Agreement and Sustainable Development Goals (SDGs) provide opportunities to align national groundwater policies with climate and carbon management agendas [8].

6. Future Research Directions

6.1 Quantifying Interactive Effects

Despite growing evidence, the interactive effects of groundwater depletion and climate variability on carbon sequestration remain poorly quantified. Future research should prioritize long-term field experiments and model simulations that integrate hydrological and carbon cycle processes. Tools like coupled hydro-biogeochemical models can capture nonlinear dynamics, such as the effects of wet–dry cycles on soil respiration.

6.2 Regional Vulnerability Assessments

Groundwater depletion and climate variability are region-specific phenomena, yet most studies remain localized or short-term. Comparative research across vulnerable hotspots—such as South Asia, Sub-Saharan Africa, and the U.S. High Plains—would provide insights into differential responses of soils and cropping systems. Integrating remote sensing, isotopic tracing, and eddy covariance techniques could help quantify spatial and temporal patterns of carbon fluxes under combined stressors.

6.3 Socioeconomic and Governance Dimensions

Much of the research has focused on biophysical processes, while socioeconomic dimensions remain underexplored. Future work should investigate how farmer behavior, water pricing policies, and land tenure arrangements mediate the impact of groundwater depletion on carbon sequestration. Similarly, understanding the role of governance frameworks in regulating both groundwater and carbon markets is crucial for designing effective interventions.

6.4 Innovations in Carbon–Water Management

Emerging technologies offer new opportunities for integrating groundwater and carbon management. Biochar application, precision irrigation, microbial inoculants, and nanomaterials represent promising interventions that warrant further testing across diverse agroecosystems. Advances in digital agriculture—using sensors, AI, and satellite data— could enable real-time monitoring of soil carbon stocks and groundwater use, facilitating adaptive management [6].

6.5 Climate Adaptation and Mitigation Synergies

Future research must explicitly examine co-benefits and trade-offs between adaptation strategies (e.g., drought-resistant crops, water harvesting) and mitigation outcomes (soil carbon storage). A better understanding of these synergies will allow policymakers to prioritize interventions that simultaneously strengthen food security and climate resilience.

7. Conclusion

Groundwater depletion and climate variability represent two of the most significant challenges to agriculture's carbon sequestration potential. Individually, they reduce crop productivity, accelerate soil organic carbon losses, and undermine soil health. Collectively, they exert synergistic and nonlinear pressures, creating feedback loops that exacerbate both water scarcity and carbon instability. Evidence from diverse agroecosystems underscores that without effective management, these dual stressors may drastically limit the role of agriculture as a carbon sink in global climate mitigation strategies. Yet, solutions exist. Sustainable groundwater management, efficient irrigation, and agroecological practices can buffer soils against carbon losses while enhancing resilience to climate variability. Policy frameworks that integrate the water–energy–carbon nexus are essential, aligning agricultural water management with global climate and development goals. At the same time, advancing research on the biophysical, socioeconomic, and governance dimensions of this issue will be critical to designing interventions that are both context-specific and scalable. Maintaining and enhancing agricultural carbon sequestration under conditions of groundwater depletion and climate variability requires a holistic, cross-disciplinary approach. By bridging hydrology, soil science, climate research, and policy, it is possible to safeguard soil carbon stocks, strengthen food security, and contribute to climate change mitigation. Agriculture, if managed sustainably, can remain a cornerstone of carbon sequestration in the Anthropocene.

References

1. Carroll, Susan A., Elizabeth Keating, Kayyum Mansoor, Zhenxue Dai, Yunwei Sun, Whitney Trainor-Guitton, Chris Brown, and Diana Bacon. "Key factors for determining groundwater impacts due to leakage from geologic carbon sequestration reservoirs." *International Journal of Greenhouse Gas Control* 29 (2014): 153-168.

2. Ranjan, S. P., Kazama, S., & Sawamoto, M. (2006). Effects of climate and land use changes on groundwater resources in coastal aquifers. *Journal of Environmental Management*, *80*(1), 25-35.

3. Baron, J. S., Hall, E. K., Nolan, B. T., Finlay, J. C., Bernhardt, E. S., Harrison, J. A., ... & Boyer, E. W. (2013). The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. *Biogeochemistry*, *114*(1), 71-92.

4. Zepp, R. G., Erickson Iii, D. J., Paul, N. D., & Sulzberger, B. (2007). Interactive effects of solar UV radiation and climate change on biogeochemical cycling. *Photochemical & Photobiological Sciences*, *6*(3), 286-300.

5. Ollinger, S. V., Aber, J. D., Reich, P. B., & Freuder, R. J. (2002). Interactive effects of nitrogen deposition, tropospheric ozone, elevated CO2 and land use history on the carbon dynamics of northern hardwood forests. *Global Change Biology*, *8*(6), 545-562.

6. Lal, R. (2003). Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical reviews in plant sciences*, *22*(2), 151-184.

7. Bornman, J. F., Barnes, P. W., Robinson, S. A., Ballaré, C. L., Flint, S. D., & Caldwell, M. M. (2015). Solar ultraviolet radiation and ozone depletion-driven climate change: effects on terrestrial ecosystems. *Photochemical & Photobiological Sciences*, *14*(1), 88-107.

8. Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of plant nutrition and soil science*, *177*(5), 651-670.

9. Elbasiouny, H., El-Ramady, H., Elbehiry, F., Rajput, V. D., Minkina, T., & Mandzhieva, S. (2022). Plant nutrition under climate change and soil carbon sequestration. *Sustainability*, *14*(2), 914.

10. Sikka, Alok K., Adlul Islam, and K. V. Rao. "Climate-smart land and water management for sustainable agriculture." *Irrigation and Drainage* 67, no. 1 (2018): 72-81.

11. Olesen, J. E., & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European journal of agronomy*, *16*(4), 239-262.

12. Abbas, F., Hammad, H. M., Fahad, S., Cerdà, A., Rizwan, M., Farhad, W., ... & Bakhat, H. F. (2017). Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. *Environmental Science and Pollution Research*, *24*(12), 11177-11191.

13. VijayaVenkataRaman, S., Iniyan, S., & Goic, R. (2012). A review of climate change, mitigation and adaptation. *Renewable and Sustainable Energy Reviews*, *16*(1), 878-897.

14. Goudriaan, J., & Unsworth, M. H. (1990). Implications of increasing carbon dioxide and climate change for agricultural productivity and water resources. *Impact of carbon dioxide, trace gases, and climate change on global agriculture*, *53*, 111-130.

15. Lal, R. (2012). Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research*, *1*(3), 199-212.

16. Hanssen, S. V., Daioglou, V., Steinmann, Z. J. N., Doelman, J. C., Van Vuuren, D. P., & Huijbregts, M. A. J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. *Nature Climate Change*, *10*(11), 1023-1029.