Review Article

Carbon Sequestration in a Changing Climate: Management Techniques and Strategic Solutions

---

ABSTRACT

Carbon sequestration in agriculture plays a critical role in mitigating climate change by capturing and storing atmospheric carbon dioxide (CO2) in soil and biomass. This process involves various strategies and management practices aimed at enhancing soil organic carbon (SOC) levels while maintaining or improving agricultural productivity. Key strategies include no-tillage or reduced tillage, which minimizes soil disturbance and promotes residue retention, thus slowing down decomposition and enhancing carbon storage. Crop rotation and the use of cover crops further contribute to carbon sequestration by diversifying root structures and improving soil health. Organic farming practices, such as applying farmyard manure and compost, provide essential organic matter that enriches soil quality and increases carbon retention. Additionally, the incorporation of deep-rooted plants and biochar enhances carbon storage in deeper soil layers, making them more resilient to climate variability. The integration of these practices not only sequesters carbon but also improves soil fertility, water retention, and overall ecosystem health.

Effective management of carbon sequestration in agricultural systems requires a holistic approach that considers local conditions, crop diversity, and sustainable land use practices. By adopting these strategies, agriculture can become a significant carbon sink, contributing to global efforts to reduce atmospheric CO2 concentrations while ensuring food security and environmental sustainability.

***Keywords**: Agriculture, Biochar, Carbon sequestration, Conservation tillage, Crop rotation, Organic farming.*

1. INTRODUCTION

The Earth's atmosphere consists of approximately 78.09% nitrogen, 20.95% oxygen, and 0.04% carbon dioxide, along with trace amounts of other gases. Carbon is an essential element in all living organisms and forms the foundation of life on Earth. It exists in various forms, such as carbon dioxide, carbonates, and organic compounds, and is continuously cycled between the atmosphere, oceans, land, and living organisms. This cycle is driven by natural processes like photosynthesis, respiration, and the dissolution and precipitation of carbonates (Grace, 2001).

However, human activities have significantly disrupted this balance, contributing to global warming and climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature has increased by 0.87°C, while the land surface air temperature has risen by 1.53°C between 1850 and 2015 (IPCC, 2014). The melting of polar ice caps and glaciers has accelerated sea-level rise, which has increased by about 20 cm over the past 170 years and is now growing at a rate of 0.8 mm per year per decade (Nerem et al., 2018; Siegert et al., 2020).

Anthropogenic emissions, particularly over the last 70 years, are largely responsible for this rapid increase in global temperatures. Greenhouse gases (GHGs) like carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are the primary drivers. CO2 levels, in particular, have soared from around 280 ppm during pre-industrial times to 416 ppm by 2021 (CO2 Earth, 2021). As CO2 can remain in the atmosphere for 3–10 centuries (Archer et al., 2009; UNFCCC, 2015), it is crucial to both drastically reduce emissions and apply carbon sequestration techniques. This requires immediate action to cut CO2 emissions and implement "negative emission" technologies to meet the goal of a decarbonized global economy by 2050 (Lal, 2008).

2. CARBON SEQUESTRATION

Carbon sequestration refers to the long-term storage of carbon dioxide or other carbon forms in oceans, soils, vegetation (especially forests), and geological formations to mitigate or delay global warming. Izaurralde et al. (2007) defined carbon sequestration as the adoption of land management practices that enhance net primary productivity, reduce the rate of heterotrophic respiration, or achieve both, leading to increased carbon storage in ecosystems. Practices like planting trees, reducing tillage intensity on cropland, and restoring degraded grasslands can boost carbon storage in plants, soils, or both.

Soil carbon sequestration, as reported by Sundermeier et al. (2005a), involves transferring carbon dioxide from the atmosphere into soils via crop residues and other organic materials in a stable form that is not immediately reemitted. This process helps offset carbon emissions from fossil fuel use and other sources while improving soil quality and promoting long-term agronomic productivity. Plants capture carbon through photosynthesis and release some of it back into the atmosphere via respiration. The carbon retained in plant tissue is eventually added to the soil when plants die and decompose, or consumed by animals. In soils, carbon primarily exists as soil organic matter (SOM), a complex mix of decomposing plant and animal tissues, microorganisms (like fungi and bacteria), and carbon bound to soil minerals. Depending on climatic conditions, vegetation types, soil texture, and drainage, carbon can either remain stored in the soil for thousands of years or be released back into the atmosphere relatively quickly.

In India, the potential for soil carbon sequestration is estimated at 39-52 million tonnes of carbon per year. Of this, 7.2-9.8 million tonnes could come from restoring degraded soils, 5-7 Tg per year from controlling erosion, 6-7 million tonnes from adopting improved agricultural management practices, and 22-26 million tonnes from the formation of secondary carbonates (Lal, 2004). According to the Indian Council of Agricultural Research (ICAR) and the National Academy of Agricultural Sciences (NAAS), around 121 million hectares of land in India are degraded, including salt-affected wastelands (Maji et al., 2010). Lal (2004) suggested that reclaiming salt-affected soils could sequester up to 2 billion tonnes of carbon. Globally, the potential for soil carbon sequestration ranges from 0.4 to 1.2 gigatonnes of carbon per year, with cropland contributing 0.4-0.8 GtC/year, degraded and desertified soil restoration contributing 0.2-0.85 GtC/year, irrigated soils contributing 0.01-0.03 GtC/year, and grasslands 0.01-0.3 GtC/year.

3. SEQUESTRATION STRATEGIES

Carbon sequestration strategies can be broadly classified into two categories: biological and non-biological. Non-biological sequestration is attained through physical and chemical reactions (Lal, 2008a). It includes oceanic sequestration, geological sequestration, and chemical sequestration by mineral carbonation. These methods, however, have limitations concerning their efficiency and the cost involved (Nogia et al., 2016). Biological sequestration refers to the capture and storage of CO2 through natural processes. In comparison to non-biological methods, biotic techniques are cost-effective and immediately applicable.

4. BENEFITS OF CARBON SEQUESTRATION IN SOILS

Soils are the largest carbon reservoir in the terrestrial carbon cycle, storing substantial amounts of soil organic carbon (SOC) derived from plant and animal matter at various stages of decomposition. The balance between the input of plant materials (like leaf and root litter) and losses from decomposition and mineralization processes determines the amount of carbon stored in soils. Carbon sequestration in soils occurs both directly and indirectly (Soil Science Society of America, 2001). Direct sequestration happens through chemical reactions that convert CO2 into inorganic carbon compounds, such as calcium and magnesium carbonates. Indirect sequestration occurs when plants capture atmospheric CO2 through photosynthesis and some of that carbon is stored as SOC during the decomposition of plant biomass.

Sequestering carbon in soils offers several benefits beyond reducing atmospheric CO2. These include improving soil quality by enhancing fertility, structure, and stability, increasing water retention, decreasing nutrient loss, reducing soil erosion, and increasing crop yields. Additionally, soils with higher carbon content can better mitigate toxic elements. However, research shows that elevated CO2 levels affect soil microbes, leading to more carbon release in nitrogen-rich soils, while nitrogen-limited soils under trees sequester more carbon. Nitrogen-based fertilizers, often used to boost tree growth, can exacerbate CO2 loss from soils (Lagomarsino, 2007).

5. MANAGEMENT TECHNIQUES FOR CARBON SEQUESTRATION IN SOILS

The stored soil carbon is vulnerable to loss through both land management change and climate change. The important strategies of soil C sequestration include the restoration of degraded soils, and the adoption of improved management practices (IMPs) of agricultural and forestry soils. Management techniques, that are successful in providing a net carbon sink in soils, include the following:

5.1 Conservation agriculture: Conservation agriculture, as defined by the Food and Agriculture Organization (FAO), is a resource-saving approach to crop production that aims to achieve sustainable, high yields while protecting the environment. Unlike traditional farming methods that often prioritize yields at the expense of the environment, conservation agriculture utilizes modern technology to enhance productivity while maintaining the ecosystem's health and integrity (Dumanski et al., 2006).

This approach has the potential to transform soils from carbon sources to carbon sinks by sequestering atmospheric carbon into the soil (Lal et al., 1998). Conservation agriculture benefits include reduced soil erosion, improved water infiltration, enhanced soil structure, and increased organic matter. It promotes biological tillage, moderates soil temperature, and suppresses weeds, all while lowering production costs and saving time. Additionally, it improves yields through timely planting, reduces diseases and pests by encouraging biodiversity, and helps lower greenhouse gas emissions (Hobbs, 2007).

5.2 Minimum/zero tillage: The primary purpose of tillage is to create a favorable soil environment for plant growth. However, it is a major factor contributing to the reduction of soil carbon stocks. When soil is tilled, the bare surface becomes vulnerable to the breakdown of soil aggregates due to the impact of raindrops. This leads to clogged soil pores, reduced water infiltration, and increased runoff, which in turn causes soil erosion. As the surface dries, it forms a crust, acting as a barrier to plant emergence (Hobbs, 2007).

The use of mouldboard plows and disc harrows is a significant cause of carbon loss from the soil, as they destroy soil aggregates and speed up the decomposition of plant residues. Shifting tillage practices can help sequester carbon in agricultural soils. Conservation tillage methods, including no-tillage, reduced tillage, and mulch tillage, can retain crop residues on the soil surface and reduce soil disturbance (Uger, 1990). Govaerts et al. (2009) noted that conservation tillage technologies aim to reduce tillage for both pre-plant and in-season operations, improving soil carbon levels, reducing soil erosion, and lowering fossil fuel consumption in farming activities.

5.3 Cover crops: Cover crops, such as legumes and small grains, are grown between regular crop production to protect and improve the soil. They enhance carbon sequestration by improving soil structure and adding organic matter. Legumes, in particular, contribute significantly to soil organic carbon due to their ability to fix atmospheric nitrogen, shed leaves, and develop substantial below-ground biomass (Ganeshamurthy, 2009). Research by McCalla (1958) demonstrated that fields with residue mulch have higher populations of beneficial organisms like bacteria, fungi, and earthworms compared to fields where residues are incorporated. Cover crops promote biological tillage through their roots, and the surface mulch provides nutrients and energy for soil organisms that help aerate and till the soil naturally.

5.4 Crop rotations or crop sequencing: Crop rotation enhances soil structure and fertility by alternating deep-rooted and shallow-rooted plants. This practice allows different crops to utilize and replenish various nutrients. For instance, a crop that depletes specific nutrients is followed by one that either returns those nutrients to the soil or uses them in different proportions. This variation in crops, helps increase soil organic matter. However, the effectiveness of crop rotation depends on the types of crops used and the rotation frequency. A key component of crop rotation is nitrogen replenishment, often achieved by incorporating green manure crops in sequence with cereals and other plants.

Organic crop rotations typically include deep-rooted legumes, which enrich the soil with nitrogen through rhizo-deposition and deep root biomass, enhancing carbon storage in deeper soil layers. This method also optimizes nitrogen use and supports integrated livestock production (Gregorich et al., 2001). Including legumes in crop rotations boosts in-situ nitrogen availability, reducing the need for synthetic nitrogen fertilizers while depositing significant carbon into the soil through root exudation.

The carbon sequestered through crop rotations primarily accumulates in the mineral-associated organic matter fraction, likely due to stabilization mechanisms involving organic matter and soil minerals, which help retain carbon over time.

5.5 Crop residue: Crop residues in India vary significantly depending on the crops grown, cropping intensity, and regional productivity. The problem of on-farm burning of residues has become more severe due to the widespread use of combined harvesters and the high cost of manual labor for residue removal (NAAS, 2012). Burning residues releases harmful gases like CO, CH4, N2O, NOx, and SO2 (Anonymous, 2012), which contribute to air pollution and disturb the soil’s microbial balance. Additionally, burning causes moisture loss and raises soil pH by producing ash rich in calcium, magnesium, and potassium ions. Instead of burning, converting crop residues to biochar could offer a sustainable alternative for soil improvement and carbon sequestration.

Leaving crop residues on the field also plays a crucial role in enhancing soil organic carbon storage. The amount of residue returned to the soil depends on the crop type, growing conditions, and agricultural practices. Using crop residues as mulch has proven beneficial, as it lowers soil temperatures and conserves water. A good agronomic practice for wheat is direct drilling into rice residue using the happy seeder. This zero-tillage method conserves soil organic matter, improves soil health, reduces tillage costs, and eliminates the need for burning, thus promoting sustainability (Singh and Sidhu, 2014).

5.6 Organic agriculture: Organic agriculture offers an environmentally sustainable approach to farming by using low external inputs while ensuring food production. In India, organic farming has a long tradition, and its practices vary across the country due to the diverse climates. Organic agriculture avoids the use of synthetic chemicals, relying instead on natural methods to enhance soil fertility and manage crops.

A major source of greenhouse gas (GHG) emissions in India comes from livestock, accounting for 64.15% of total emissions due to enteric fermentation and improper manure management (Anonymous, 2007). Traditionally, cow dung is used as fuel or collected in heaps, where anaerobic fermentation leads to methane release. This can be mitigated by converting dung and farm waste into manure. Farmyard manure (FYM) is a valuable organic input that improves soil fertility. Studies by Li et al. (1994) and Gregorich et al. (1998) have shown that manure application leads to substantial carbon sequestration, especially in clay soils, and helps retain carbon for longer periods.

Organic farming plays a key role in climate change mitigation by sequestering carbon in soils and reducing GHG emissions, as it avoids burning biomass and reduces the need for synthetic nitrogen fertilizers. Additionally, organic practices improve soil quality and resilience, making soils less vulnerable to extreme weather events while conserving energy by eliminating the use of chemical fertilizers.

5.7 Grasses and forages: Deep-rooted grasses enhance carbon sequestration by assimilating atmospheric CO2 through photosynthesis and transporting the carbon to deeper soil layers. Their fast-growing, fibrous root systems penetrate larger soil volumes, making them more efficient at trapping carbon compared to leguminous cover crops (Lal et al., 1999a). The high root production in grasses not only replenishes soil organic carbon (SOC) but also increases soil organic matter (SOM) in pastures and fallows. Additionally, grassroot debris decomposes more slowly than shoots due to its higher lignin content, contributing to long-term carbon storage (Woomer et al., 1994).

5.8 Rotational grazing: Rotational grazing can significantly enhance soil carbon stocks, contrary to the common perception that grazing reduces residue availability for carbon sequestration. When managed properly, this practice positively influences soil carbon levels. By introducing more productive grass species and legumes, improved grasslands can achieve high rates of carbon sequestration. Additionally, optimizing nutrient management and implementing irrigation can further boost productivity and carbon storage (Verchot and Singh, 2009).

Rotational grazing involves subdividing pastureland into distinct grazing units, allowing livestock to graze in a controlled manner throughout the season. This method keeps pastures in a lush vegetative state, improves grass quality, and decreases carbon dioxide emissions by enhancing the soil's carbon storage capacity. Concentrating livestock in smaller paddocks for short durations promotes even grazing, enabling roots to penetrate deeper into the soil. As a result, this practice not only enhances soil health but also contributes to effective carbon sequestration over time.

5.9 Biochar or Black carbon: Biochar, a solid material produced from the carbonization of biomass, is emerging as a promising strategy for permanent carbon storage. According to Lehmann et al. (2006), the concept of biochar has gained traction alongside growing concerns about soil management and carbon sequestration. Unlike charcoal, which is primarily used as fuel, biochar is specifically designed for atmospheric carbon capture and soil application.

Durenkamp et al. (2010) define biochar as charcoal derived from the pyrolysis of biomass feedstock, including plant materials, crop residues, and non-stem logging residues. This process creates an excellent soil amendment that serves as a cost-effective source of organic carbon while enhancing water retention and providing a habitat for beneficial microbes.

Research by Zimmerman (2010) and Roberts et al. (2010) indicates that applying biochar to soil can significantly increase soil organic carbon (SOC) levels. The conversion of biomass to biochar retains approximately 50% of the initial carbon, compared to a mere 3% retention from burning and less than 10-20% from biological decomposition over 5-10 years (Lehmann et al., 2006).

The advantages of biochar include:

1. Reduced fertilizer use, leading to lower greenhouse gas emissions during fertilizer production.
2. Enhanced soil microbial populations, promoting further carbon sequestration.
3. Nitrogen retention, which helps decrease nitrous oxide emissions.
4. Conversion of agricultural waste into biochar, thereby minimizing methane emissions.

Overall, biochar presents a multifaceted approach to improving soil health while combating climate change.

5.10 Land use change and soil amendments: Land use patterns in India are primarily dominated by cropland, followed by forestland. According to Lal (2001), converting degraded agricultural soils and other land uses into forests or perennial land uses can significantly enhance the soil organic carbon (SOC) pool. The effectiveness and rate of SOC sequestration through afforestation are influenced by various factors, including climate, soil type, species selection, and nutrient management practices. Mann (1986) estimated that converting non-cropland areas, such as grasslands or forests, to cropland could release approximately 750 kg of carbon per hectare annually during the first 20 years, emphasizing the carbon emissions associated with changes in land use.

Soil amendments, which consist of leftover residues from various processes, offer numerous benefits when incorporated into the soil. Common amendments include municipal biosolids, animal manures, wood ash, composted food scraps, and agricultural by-products. These amendments help restore soil quality by balancing pH levels, adding organic matter, improving water retention, and reestablishing microbial communities, while also reducing soil compaction. Additionally, the application of soil amendments can mitigate CO2 and methane emissions that would typically occur if industrial byproducts, like biosolids, were disposed of improperly. Effective land use change and soil amendments are vital for enhancing carbon sequestration and improving soil health.

5.11 Inorganic fertilizer: Fertilization is crucial for enhancing crop production and increasing plant biomass, ultimately boosting carbon sequestration. Lal et al. (1999) highlighted fertilizer application as an effective method for carbon sequestration. However, the CO2 emissions from fossil fuel combustion during nitrogen fertilizer production and application can offset its benefits, and excess nitrogen can run off into waterways, causing ecological harm.

6. DISCUSSION

The study on carbon sequestration in agriculture highlights the importance of soil management techniques in mitigating climate change by enhancing soil organic carbon (SOC) levels. This research is especially relevant to agricultural territories in Latin America, such as Panama (Montenegro et al. 2021; Pitti et al. 2021), Colombia (Rodriguez et al. 2023a), and Venezuela (Olivares, 2016; Olivares et al. 2022a; 2022b), where carbon sequestration practices can help address both climate impacts (Zingaretti et al. 2016; Viloria et al. 2023; Paredes-Trejo et al. 2023) and soil degradation (Olivares et al. 2011). No-tillage and reduced tillage, for example, are essential practices that minimize soil disturbance and increase carbon retention (Araya-Alman et al. 2020; Lobo et al. 2023). In Colombia, similar conservation tillage practices have been shown to improve carbon storage in banana and maize systems (Rodriguez et al. 2023b), while also enhancing soil health and reducing erosion (Olivares et al. 2022c). Such comparisons demonstrate that techniques highlighted in the study can be adapted to local contexts in Latin America to promote sustainable agricultural development while addressing climate challenges (Campos et al. 2023; Campos, 2023).

The integration of crop rotation and the use of cover crops as outlined in the study also aligns with Latin American agricultural strategies aimed at improving soil quality and resilience to climate variability (Campos, 2014b; 2014c). In Venezuela and Panama, where soil degradation is often exacerbated by monoculture and intensive farming practices (López and Olivares, 2019), crop diversification and the use of cover crops can improve soil structure (López et al. 2019), boost nutrient cycling, and enhance moisture retention (Montenegro et al. 2020). This mirrors findings from studies in Colombia’s highland areas, where the inclusion of cover crops and diversified rotations has significantly improved soil organic carbon levels and water retention, particularly in coffee and vegetable production systems (Campos, 2014a). These practices not only contribute to carbon sequestration but also support the water-soil-plant relationship, which is critical for maintaining agricultural productivity under changing climate conditions (Olivares et al. 2015; Olivares et al. 2017a; Olivares and Zingaretti, 2019).

Organic farming practices, such as the use of manure and compost, are particularly effective in increasing carbon sequestration and improving soil fertility. In Panama and Venezuela (Hernandez et al. 2020; Hernandez and Olivares, 2020), where organic matter depletion is a concern due to deforestation and overuse of synthetic inputs, the application of farmyard manure and compost can restore soil organic carbon levels, as indicated by the study. Similarly, the incorporation of biochar and deep-rooted plants has been identified as a promising technique for sequestering carbon in deeper soil layers in Latin America (Hernandez and Olivares, 2019). In Colombia, biochar use has shown positive outcomes in enhancing soil fertility and increasing carbon retention, supporting both climate mitigation and soil restoration goals (Hernandez et al. 2018a; 2018b). Overall, the study’s findings resonate strongly with ongoing efforts in Latin America to enhance soil quality and resilience, providing a blueprint for scaling carbon sequestration practices in the region (Olivares et al. 2017b).

6. CONCLUSION

Carbon sequestration is intricately linked to soil management practices. Zero or no-tillage, combined with the retention of crop residues on the soil surface, effectively enhances carbon storage while increasing water use efficiency and reducing fossil fuel consumption. When crop residues are left on the surface, only a small portion contacts the soil and microbes, resulting in slower decomposition due to limited oxygen availability. In contrast, incorporating crop residues into the soil accelerates decomposition and CO2 release, making residue retention a preferable strategy for carbon sequestration.

Crop rotation is another beneficial practice that promotes carbon sequestration. By alternating different crops, the rate of soil organic carbon (SOC) accumulation can increase at various depths, as each crop species possesses distinct root systems that explore different soil layers. Additionally, applying manures serves as an effective means of enhancing organic matter in the soil, leading to a greater carbon pool. Manures are generally more resistant to microbial decomposition than plant residues, resulting in higher carbon storage for the same carbon input.

Organic agriculture prioritizes the health of soils and ecosystems by utilizing ecological processes and biodiversity, minimizing reliance on harmful inputs. Utilizing farmyard manure (FYM) is a valuable practice for enhancing soil fertility, while also promoting aggregate formation and stabilization, which aids long-term carbon storage. However, a notable drawback of manure use is carbon loss due to the respiration and growth needs of livestock, which can also produce significant methane emissions, a potent greenhouse gas.

To mitigate these emissions, balanced fertilization with nitrogen, phosphorus, potassium (NPK), and micronutrients can be integrated into organic farming practices. Moreover, developing deep-rooted crops and grasses through hybridization can enhance carbon storage in deeper soil layers. Remarkably, 30-50% of the carbon fixed during photosynthesis in many plants is translocated below ground, where it contributes to root growth and is lost to the surrounding soil through rhizo-deposition.

Additionally, biochar is a promising carbon storage solution, capable of retaining carbon in the soil for hundreds to thousands of years. Its application not only improves soil fertility but also stimulates plant growth, ultimately leading to increased biomass and enhanced carbon dioxide consumption.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

REFERENCES

Anonymous. (2012). India Second National Communication to the United Nations Framework Convention on Climate Change. Ministry of Environment and Forests, Government of India:65

Araya-Alman, M., Olivares, B., Acevedo-Opazo, C. et al. (2020). Relationship Between Soil Properties and Banana Productivity in the Two Main Cultivation Areas in Venezuela. J Soil Sci Plant Nutr.; 20 (3): 2512-2524. https://doi.org/10.1007/s42729-020-00317-8

Archer, D., Eby, M., Brovkin, V., et al., (2009). Atmospheric lifetime of fossil fuel carbon dioxide. Annu. Rev. Earth Planet. Sci. 37, 117–134.

Campos, B. O. (2023). Banana Production in Venezuela: Novel Solutions to Productivity and Plant Health. Springer Nature. https://doi.org/10.1007/978-3-031-34475-6

Campos, B. O. O., Araya-Alman, M., &Marys, E. E. (2023).Sustainable Crop Plants Protection: Implications for Pest and Disease Control (p. 200). MDPI-Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/books978-3-0365-9150-6

Campos, B. (2014a). Relationship of nature climate and spirituality of indigenous communities state agricultural Anzoátegui Kariña, Venezuela. Revista Tiempo y Espacio. 61 (2): 129-150. https://n9.cl/wx7q2

Campos, B. (2014b). Systematization of traditional knowledge and ancestral ethnicity kari'ña in Anzoategui state, Venezuela. Revista de Investigación. 82 (38): 89-102. https://n9.cl/cmzoy

Campos, B. (2014c). Application of Principal Component Analysis (PCA) in Socio-Environmental Diagnosis. Case: The Campo Alegre Sector, Simón Rodríguez Municipality, Anzoátegui. RevistaMulticiencias. 14 (4): 364 – 374. https://www.redalyc.org/articulo.oa?id=90433839011

Dumanski J, Peiretti R, Benites J R, McGarry D and Pieri C. (2006). The paradigm of conservation agriculture.*Proc. World Assoc. Soil Water Conserv*. P1 58–64.
Durenkamp M, Luo Y and Brookes P C. (2010). Impact of black carbon addition to soil on the determination of soil microbial biomass by fumigation extraction.*Soil Biol. Biochem.* **42:** 2026-2029.

Ganeshamurthy A N. (2009). Soil changes following long-term cultivation of pulses. *J. Agric. Sci.* **147:** 699-706

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre K D, Dixon J and Dendooven L. (2009). Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality. *Crit. Rev.Plant Sci*. **28:**97–122

Grace J. (2001). The Global Carbon Cycle.In Levin S. (Ed.) *Encyclopedia of Biodiversity. Volume I*. Orlando, FL: Academic Press.

Gregorich E G, Drury C F and Baldock J A. (2001). Changes in soil carbon under long-term maize in monoculture and legume-based rotation.*Can. J. Soil. Sci.* **81:** 21–31.

Gregorich E G, Rochette P, McGuire S, Liang B C and Lessard R. (1998). Soluble organic carbon and carbon dioxide fluxes in maize fields receiving spring-applied manure.*J.Env. Qual.* **27:** 209–214.

Hernández, R., Olivares, B., (2020). Application of multivariate techniques in the agricultural land's aptitude in Carabobo, Venezuela. Tropical and Subtropical Agroecosystems, 23(2):1-12. https://n9.cl/zeedh

Hernández, R; Olivares, B. Arias, A; Molina, JC., Pereira, Y. (2018a). Agroclimatic zoning of corn crop for sustainable agricultural production in Carabobo, Venezuela. RevistaUniversitaria de Geografía. . 27 (2): 139-159. https://n9.cl/l2m83

Hernandez, R., Olivares, B., Arias, A, Molina, JC., Pereira, Y. (2020). Eco-territorial adaptability of tomato crops for sustainable agricultural production in Carabobo, Venezuela. Idesia. 38(2):95-102. http://dx.doi.org/10.4067/S0718342920200002000095

Hernández, R; Olivares, B., Arias, A; Molina, JC., Pereira, Y. (2018b). Identification of potential agroclimatic zones for the production of onion (Allium cepa L.) in Carabobo, Venezuela. Journal of the Selva Andina Biosphere., 6 (2): 70-82. http://www.scielo.org.bo/pdf/jsab/v6n2/v6n2_a03.pdf

Hernández, R. Olivares, B. (2019). Ecoterritorial sectorization for the sustainable agricultural production of potato (Solanum tuberosum L.) in Carabobo, Venezuela. Agricultural Science and Technology. 20(2): 339-354. https://doi.org/10.21930/rcta.vol20_num2_art:1462

Hobbs P R. (2007). Conservation agriculture: what is it and why is it important for future sustainable food production. *J. Agric. Sci.* **145:** 127–137.

IPCC, (2014). Climate change 2014 synthesis report: a report of the intergovernmental panel on climate change. Geneva, Switzerland.

Izaurralde R C, Williams J R, Post W M, Thomson A M, McGill WB, Owens L and Lal R. (2007). Long-term modeling of soil C erosion and sequestration at the small watershed scale. *Climatic Change* **80**(1):73-90.

Lagomarsino A. (2007). Structural andFunctional Diversity of Soil Microbes is Affected by Elevated [CO2] and N Addition in a Poplar Plantation. *J. Soils Sediments.* **7**(6): 399–405.

Lal R, Hassan H M and Dumanski J. (1999a). Desertification control to sequester carbon and mitigate the greenhouse effect. In: *Carbon sequestration in soils: Science monitoring and beyond* eds. N. Rosenberg R.C. Izaurralde and E.L. Columbus Ohio: Malone Battelle Press.

Lal R, Kimble JM, Follett RE, Cole CV. (1998). The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Sleeping Bear Press, Chelsea, MI, pp. 128.

Lal R. (2001). The potential of soil carbon sequestration in forest ecosystem to mitigate the greenhouse effect. In: Lal R. (Ed.), *Soil Carbon Sequestration and the Greenhouse Effect.*Soil Science Society of America Special Publication, 57 Madison, WI.

Lal R. (2004). Soil carbon sequestration in India.*Climatic Change* **65:** 277–296
Lal R. Kimble J M, Follett R F, Cole C V. (1999b). *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect.*Boca Raton FL: Lewis Publishers.

Lal, R., (2008a). Carbon sequestration. Philos. Trans. R. Soc. B 363, 815–830. https://doi.org/10.1098/rstb.2007.2185.

.Lobo, D; Olivares, B; Rey, J.C; Vega, A; Rueda-Calderón, A. (2023). Relationships between the Visual Evaluation of Soil Structure (VESS) and soil properties in agriculture: A meta-analysis. Scientia agropecuaria, ; 14 - 1, 67 - 78. https://doi.org/10.17268/sci.agropecu.2023.007

López, M. Olivares, B. (2019). Normalized Difference Vegetation Index (NDVI) applied to the agricultural indigenous territory of Kashaama, Venezuela. UNED Research Journal. 11(2): 112-121. https://doi.org/10.22458/urj.v11i2.2299

López-Beltrán, M., Olivares, B., Lobo-Luján, D. (2019). Changes in land use and vegetation in the agrarian community Kashaama, Anzoátegui, Venezuela: 2001-2013. RevistaGeográfica De América Central. 2(63):269-291. https://doi.org/10.15359/rgac.63-2.10

Lehmann J, Gaunt JandRondon M. (2006). Bio-char sequestration in terrestrial ecosystems - A review.*Mitigation and Adaptation Strategies for Global Change* **11:** 403–427.

Li CS, Frolking S, Harris R and Rolking S. (1994). Modeling carbon biogeochemistry in agricultural soils.*Glob.Biogeo.Cyc*. **8:** 237 - 254.

Maji A K, Obi Reddy G P and Sarkar D. (2010). Degraded and Wastelands of India:Status and Spatial Distribution, ICAR, New Delhi, pp. 167.

Mann L K. (1986). Changes in soil carbon storage after cultivation.*Soil Sci*. **142:** 279–288

McCalla T M. (1958). Microbial and related studies of stubble mulching. *J. Soil Water Conserv.* **13:** 255–258.

Montenegro, E., Pitti-Rodríguez, J, Olivares-Campos, B. Identification of the main subsistence crops of Teribe: a case study based on multivariate techniques. Idesia (Arica), 2021. 39(3), 83-94. https://dx.doi.org/10.4067/S0718-34292021000300083

Montenegro Gracia, E. J. M., Rodríguez, J. E. P., & Campos, B. O. O. (2020). Adaptation to climate change in indigenous food systems of the Teribe in Panama: a training based on

CRISTAL 2.0. Revista Luna Azul, (51), 182-197. https://www.redalyc.org/journal/3217/321770011010/321770011010.pdf.

NAAS (2012). Management of Crop Residues in the Context of Conservation Agriculture. Policy Paper No. 58, National Academyof Agricultural Sciences, New Delhi. 12 p.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci. 115, 2022–2025. https://doi.org/10.1073/pnas.1717312115.

Nogia, P., Sidhu, G.K., Mehrotra, R., Mehrotra, S., (2016). Capturing atmospheric carbon: biological and nonbiological methods. Int. J. Low Carbon Technol. 11, 266–274.

Olivares, B.O.; Rey, J.C.; Perichi, G.; Lobo, D. (2022a). Relationship of Microbial Activity with Soil Properties in Banana Plantations in Venezuela. Sustainability 14, 13531. https://doi.org/10.3390/su142013531

Olivares B, Rey JC, Lobo D, Navas-Cortés JA, Gómez JA, Landa BB. (2022b). Machine Learning and the New Sustainable Agriculture: Applications in Banana Production Systems of Venezuela. Agricultural Research Updates. 42, 133 - 157. Nova Science Publishers, Inc

Olivares, B. (2016). Description of soil management in agricultural production systems in the Hamaca de Anzoátegui sector, Venezuela. La Granja: Revista de Ciencias de la Vida. 23(1): 14–24. https://n9.cl/ycp08

Olivares, B., Verbist, K., Lobo, D., Vargas, R. y Silva, O. (2011). Evaluation of the USLE model to estimate water erosion in an Alfisol. Journal of Soil Science and Plant Nutrition of Chile. 11 (2):71-84. http://dx.doi.org/10.4067/S0718-95162011000200007

Olivares, B.O., Calero, J., Rey, J.C., Lobo, D., Landa, B.B., Gómez, J. A. (2022c). Correlation of banana productivity levels and soil morphological properties using regularized optimal scaling regression. Catena,; 208: 105718. https://doi.org/10.1016/j.catena.2021.105718

Olivares, B., Lobo, D., Verbist, K. (2015). Application USLE model on erosion plots under soil conservation practices and water in San Pedro de Melipilla, Chile. Revista Ciencia e Ingeniería. 36 (1):3-10. https://www.redalyc.org/pdf/5075/507550627001.pdf.

Olivares, B., Zingaretti, M.L. (2019). Aplicación de métodos multivariados para la caracterización de periodos de sequía meteorológica en Venezuela. Revista Luna Azul. 48, 172:192. http://dx.doi.org/10.17151/luaz.2019.48.10

Olivares, B., Lobo, D., Cortez, A., Rodríguez, M.F., Rey, J.C. (2017a). Socio-economic characteristics and methods of agricultural production of indigenous community Kashaama, Anzoategui, Venezuela. Rev. Fac. Agron. (LUZ) 34 (2): 187-215. https://n9.cl/p2gc5

Olivares, B., Cortez, A., Parra, R., Lobo, D., Rodríguez, M.F, Rey, J.C. (2017b). Evaluation of agricultural vulnerability to drought weather in different locations of Venezuela. Rev. Fac. Agron. (LUZ) 34 (1): 103-129. https://n9.cl/d827w

Paredes-Trejo, F., Olivares, B. O., Movil-Fuentes, Y., Arevalo-Groening, J., and Gil, A. (2023). Assessing the Spatiotemporal Patterns and Impacts of Droughts in the Orinoco River Basin Using Earth Observations Data and Surface Observations. Hydrology, 10(10), 195. https://doi.org/10.3390/hydrology10100195

Pitti, J. E.., Olivares, B. O., Montenegro, E. J., Miller, L., &Ñango, Y. (2021). The role of agriculture in the Changuinola District: A case of applied economics in Panama. Tropical and Subtropical Agroecosystems, 25(1). http://dx.doi.org/10.56369/tsaes.3815.

Roberts K G, Gloy B A, Joseph S, Scott N R and Lehmann J. (2010). Life cycle assessment of biochar systems: estimated the energetics, economic and climate change potential. *Environ. Sci. Technol.* **41:** 827–833

Rodríguez-Yzquierdo, G.; Olivares, B.O.; González-Ulloa, A.; León-Pacheco, R.; Gómez-Correa, J.C.; Yacomelo-Hernández, M.; Carrascal-Pérez, F.; Florez-Cordero, E.; Soto-Suárez, M.; Dita, M.; et al..(2023a). Soil Predisposing Factors to Fusarium oxysporum f.sp Cubense Tropical Race 4 on Banana Crops of La Guajira, Colombia. Agronomy, 13, 2588. https://doi.org/10.3390/agronomy13102588.

Rodríguez-Yzquierdo, G.; Olivares, B.O.; Silva-Escobar, O.; González-Ulloa, A.; Soto-Suarez, M.; Betancourt-Vásquez, M. (2023b). Mapping of the Susceptibility of Colombian Musaceae Lands to a Deadly Disease: Fusarium oxysporum f. sp. cubense Tropical Race 4. Horticulturae 9, 757. https://doi.org/10.3390/horticulturae9070757.

Siegert, M., Alley, R.B., Rignot, E., Englander, J., Corell, R., (2020). Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth 3, 691–703. https://doi.org/10.1016/j.oneear.2020.11.002.

Singh Y and Sidhu H S. (2014). Management of Cereal Crop Residues for Sustainable Rice-Wheat Production System in the Indo-Gangetic Plains of India.*Proc Indian NatnSci Acad.* **80:** 95-114

Soil Science Society of America, (2001). Carbon Sequestration: Position of the Soil Science Society of America (SSSA). SSSA, Madison, WI.Available at www.soils.org/pdf/ pos_paper_carb_seq.pdf.

Sundermeier A, Reeder Rand Lal R. (2005 a) Soil Carbon Sequestration—Fundamentals. Extension Fact sheet.Food Agricultural and Biological Engineering, Ohio State University, USA. AEX-510-505:1

UNFCCC, (2015). Report of the conference of the parties on its twenty-first session. Paris.
Unger P W. (1990). Conservation tillage systems.*Adv. Soil Sci.*, **13:** 27–68.

Verchot LV and Singh VP (2009). Carbon Sequestration Opportunities with Smallholder Communities: Forestry, Agriculture and Agro-Forestry. In: 4th World Congress on Conservation Agriculture 4-7th February, 2009 at New Delhi: 351-361.

Viloria, J.A.; Olivares, B.O.; García, P.; Paredes-Trejo, F.; Rosales, A. (2023). Mapping Projected Variations of Temperature and Precipitation Due to Climate Change in Venezuela. Hydrology, 10, 96. https://doi.org/10.3390/hydrology10040096.

Woomer P L, Martin A, Albrecht A, Resck D V S and Scharpenseel H W. (1994). The importance of management of soil organic matter in the tropics.*In*P.L. Woomer and M.J. Swift, eds. *Biological management of tropical soil fertility*, pp. 74–80. Chichester, UK, John Wiley.

Zimmeman A R. (2010). Abiotic and microbial oxidation of laboratory-based black carbon (biochar).*Environ. Sci. Technol.* **44:** 1295–1301.

Zingaretti, M.L., Olivares, B., Demey Zambrano, J.A. &Demey, J.R. (2016). Typification of agricultural production systems and the perception of climate variability in Anzoátegui, Venezuela. Revista FAVE - CienciasAgrarias 15 (2): 39-50. https://doi.org/10.14409/fa.v15i2.6587.