Enhancing carbon sequestration in drylands through silvopastoral systems

Gonzalez Quintero, R[1]; Notenbaert, A[1]; Vinceti, B[2]; Van Der Hoek, R[1]; Isiaho, G[1]; Herrera Calvo, PM[3]

[1]International Center for Tropical Agriculture (CIAT), [2]Bioversity International, [3]Food and Agriculture Organization of the United Nations (FAO)

Key words: Sustainable land management; Climate change mitigation.

Abstract

Drylands, spanning over 40% of the Earth's surface, sustain two billion people, half the global livestock population, and rich biodiversity. They are crucial carbon reservoirs but are highly susceptible to land degradation, emphasizing the need for sustainable management. Silvopastoral systems (SPS) present a promising approach to balance productivity with environmental gains. However, the carbon sequestration potential of SPS in drylands remains underexplored.

To address this knowledge gap, the FAO, in partnership with the Alliance of Bioversity International and CIAT, has launched a comprehensive global assessment on enhancing carbon sequestration in drylands through SPS. This initiative aims to provide evidence-based strategies for sustainable planning, management, and restoration of drylands. This study encompasses an integrative methodology combining literature reviews, case studies, and scenario modelling to evaluate current carbon reserves and forecast future potential under varying intensification, climatic, and policy contexts. Outputs include a guide to best practices and a robust monitoring framework.

These efforts will culminate in a detailed report offering actionable recommendations for policymakers, government bodies, and institutions. Collaboration with the FAO's Committee on Forestry (COFO) will ensure the development of tailored, country-specific strategies to maximize the sequestration potential of drylands via SPS. Countries will receive targeted support for designing and implementing SPS as tools for Sustainable Land Management, contributing to climate mitigation, resilience, and livelihood enhancement.

This paper highlights the findings so far, emphasizing evidence, best practices, and lessons learned. It underscores the potential of SPS to enhance carbon sequestration while supporting sustainable management and restoration. By focusing on practical strategies for leveraging SPS, it will underpin actionable recommendations to address climate adaptation and mitigation challenges, fostering the rejuvenation of these critical ecosystems and strengthening global resilience against climate change.

Introduction

Drylands cover about 41% of the Earth's surface, according to the Thornthwaite classification, and face increasing pressures from climate change and population growth (Yan et al., 2024). The livestock sector, a significant driver of land degradation, contributes 9% of anthropogenic carbon dioxide (CO_2) emissions globally, largely due to deforestation and land use changes for pasture and feed crops (Mohammed and Naqvi, 2011; Singh et al., 2017). Additionally, livestock account for 35–44% of anthropogenic methane emissions (Yusuf et al., 2012).

Carbon sequestration has emerged as a critical strategy to offset rising atmospheric CO_2 levels. SPS, multifunctional systems combining herbage, shrubs, trees, and grazing animals, present a promising sustainable land management approach. These systems not only boost productivity but also deliver ecosystem and climatic benefits by enhancing carbon storage in biomass and soil organic carbon (Aryal et al., 2019). Compared to open grasslands, SPS are particularly effective in increasing carbon storage and fostering ecosystem resilience (Feliciano et al., 2018).

Globally, SPS cover approximately 450 million hectares, accounting for 28% of agroforestry systems (Nair, 2012). Their adaptability to diverse environmental conditions and socio-economic needs makes them valuable tools for climate adaptation and sustainable development. These systems integrate diverse practices, such as grazing under tree cover, live fences, and protein banks, enabling tailored applications across regions.

This study explores the potential of SPS to enhance carbon sequestration in drylands. It aims to provide evidence-based strategies for sustainable planning, management, and restoration while addressing knowledge gaps. By evaluating current reserves and forecasting future potential, the study offers the evidence-base for designing actionable recommendations to support global climate resilience and sustainable land stewardship.

Methods

A systematic review was conducted following the methodology of Tranfield et al. (2003), comprising three stages: planning, conducting, and reporting. Studies were screened based on abstracts, full texts, and additional literature identified through snowballing methods.

To identify studies on the carbon sequestration potential of silvopastoral systems in drylands, the following search strings were used: ("silvopastoral*" OR "silvo-pastoral*" OR "agrosilvopastoral*" OR ("grazing*" AND "tree*") OR ("agroforest*" AND "livestock") OR ("pasture*" AND "tree*")) AND ("dryland*" OR "arid" OR "semi-arid" OR "desert") AND ("carbon*" OR "greenhouse gas emission*" OR "GHG*" OR "mitigation"). Boolean operators combined terms to refine searches.

Searches included published journals, bibliographic databases, conference proceedings, industry trials, and grey literature. Key sources included ScienceDirect, Web of Science, Dimensions Research, Google Scholar, and ResearchGate. Grey literature was further identified through manual reference checks, Google Scholar's cited-in function, and targeted searches. Duplicate records were manually removed.

Inclusion criteria required studies to provide quantitative carbon sequestration data for above-ground, below-ground biomass, or soil organic carbon in silvopastoral systems within drylands (annual rainfall <900mm) or areas classified as Hyper-arid, Arid, Semi-arid, or Dry sub-humid (AI <0.65) (Zomer et al., 2022). Publications needed to be recent (2003–2023), peer-reviewed, or reliable grey literature with English-language abstracts. Populist publications and inaccessible records were excluded.

Studies underwent a three-tier screening process—title, abstract, and full text—to ensure only the highest quality evidence informed the review.

Results

The systematic review has so far analysed 62 publications, highlighting diverse SPS arrangements and their contributions to carbon sequestration. Dispersed trees and shrubs in pastures were the most frequently studied arrangement, followed by grazing in timber systems, traditional SPS[10], and live fences. (Ibrahim et al., 2005; Nahed-Toral et al., 2013). These configurations vary in their structure and functionality, yet all contribute to carbon storage in above-ground biomass, below-ground biomass, and soil organic carbon. The adaptability of these arrangements allows them to thrive in diverse ecological conditions while addressing local socio-economic needs.

Dispersed trees and shrubs in pastures demonstrated a broad capacity for carbon sequestration, with total carbon stock values ranging from 60 to 183 Mg C/ha. This variation in carbon stocks is influenced by multiple factors, including soil properties, climate, tree species composition, and grazing intensity.

These systems truly bolster above-ground biomass, which ranged from 9 to 47 Mg C/ha across SPS arrangements, with grazing in timber systems often contributing to the higher end of this spectrum. Below-ground biomass, a critical component of carbon storage in SPS, ranged from 5 to 66 Mg C/ha, with traditional SPS and live fences providing notable contributions to below-ground carbon pools.

Soil organic carbon, often the largest carbon pool in SPS, ranged from 13 to 195 Mg C/ha, with systems integrating trees and shrubs, such as dispersed configurations and live fences, showing high values. Annual carbon accumulation spanned from 0.3 to 8 Mg C/ha/year, with live fences and grazing in timber arrangements contributing to dynamic carbon cycling. CO_2 sequestration rates across all arrangements were substantial, averaging approximately 1 Mg CO_2 eq/ha/year, with some systems, particularly those with denser tree components, peaking at 3.5 Mg CO_2 eq/ha/year.

Discussion

This study highlights the critical role of SPS in addressing global challenges such as climate change, land degradation, and food security. By integrating trees, shrubs, herbaceous vegetation and livestock, SPS create multifunctional ecosystems that deliver environmental and socio-economic benefits. Beyond their capacity for carbon sequestration, SPS contribute to biodiversity conservation, soil health, and water quality, making them essential components of sustainable land management strategies. Furthermore, SPS adoption has shown to improve livestock productivity by reducing heat stress, improving water availability and enhancing feed quality, contributing to higher milk yields and weight gains and reducing greenhouse gas emissions (López-Santiago et al., 2024; Rivera et al., 2024)

A critical insight from this research is the versatility of SPS configurations in achieving region-specific goals. Dispersed trees and shrubs in pastures, grazing in timber systems, and live fences are adaptable arrangements capable of thriving across diverse ecological conditions while increasing carbon storage. These variations influence carbon sequestration potential, with humid environments typically storing more carbon due to increased biomass productivity, while arid regions depend on drought-resistant species for below-ground carbon accumulation (López-Santiago et al., 2019). The influence of soil type is also critical, as finer-textured soils retain more organic carbon, whereas sandy soils require additional organic inputs to enhance sequestration potential. Additionally, moderate grazing supports soil structure and nutrient cycling, making SPS viable under varying grazing intensities (Howlett et al., 2011).

There are, however, several barriers to widespread adoption of SPS adoption. Financial constraints, limited technical knowledge, unsuitability of land to host trees, incompatible livestock management practices and land tenure issues impede their scalability. Addressing these requires targeted policies, adapted financial tools (such as

[10] Traditional silvopastoral systems integrate native trees, shrubs, and pastures with grazing livestock, often following low-input management techniques and natural regeneration. Unlike intensive SPS, traditional systems rely more on native vegetation, less on external inputs, and foster a balance between production and ecosystem services.

subsidies and low-interest loans), market-based incentives like carbon credit programs, and capacity-building initiatives tailored to local needs. Bessi et al. (2024) emphasized the importance of integrating SPS into national policies to maximize their impact on both environmental restoration and socio-economic development.

In conclusion, silvopastoral systems exemplify the convergence of ecological restoration, integrated climate mitigation and adaptation, and agricultural productivity enhancement. By integrating carbon sequestration with food security and ecosystem restoration, SPS offer a viable solution for mitigating climate change and fostering socio-economic resilience. Their strategic implementation, particularly in dryland regions, will play a pivotal role in global sustainable development efforts.

Acknowledgements
This work was carried out as part of the One CGIAR Initiative on Livestock and Climate (L&C). We thank all donors who globally support our work through their contributions to the CGIAR System. The views expressed in this document may not be taken as the official views of these organizations.

This global assessment is also part of the collaborative effort that FAO's COFO Working group on Drylands is developing towards a transformational approach to Drylands' forests and agrosilvopastoral systems for restoration and sustainable management.

References
Aryal, D.R., Gómez-González, R.R., Hernández-Nuriasmú, R., Morales-Ruiz, D.E., 2019. Carbon stocks and tree diversity in scattered tree silvopastoral systems in Chiapas, Mexico. Agroforestry Systems 93, 213–227. https://doi.org/10.1007/S10457-018-0310-Y/TABLES/5

Aynekulu, E., Suber, M., van Noordwijk, M., Arango, J., Roshetko, J.M., Rosenstock, T.S., 2020. Carbon Storage Potential of Silvopastoral Systems of Colombia. Land 2020, Vol. 9, Page 309 9, 309. https://doi.org/10.3390/LAND9090309

Bessi, D., Bernardi, A.C. de C., Pezzopane, J.R.M., Tanaka, M.O., 2024. Decomposition and stabilization of the organic matter in integrated livestock production systems. Agroforestry Systems 98, 2275–2292. https://doi.org/10.1007/S10457-024-01044-0/FIGURES/5

Feliciano, D., Ledo, A., Hillier, J., Nayak, D.R., 2018. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254, 117–129. https://doi.org/10.1016/J.AGEE.2017.11.032

Filho, J.F.L., de Oliveira, H.M.R., de Souza Barros, V.M., dos Santos, A.C., de Oliveira, T.S., 2024. From forest to pastures and silvopastoral systems: Soil carbon and nitrogen stocks changes in northeast Amazônia. Science of The Total Environment 908, 168251. https://doi.org/10.1016/J.SCITOTENV.2023.168251

Howlett, D.S., Mosquera-Losada, M.R., Nair, P.K.R., Nair, V.D., Rigueiro-Rodríguez, A., 2011. Soil Carbon Storage in Silvopastoral Systems and a Treeless Pasture in Northwestern Spain. J Environ Qual 40, 825–832. https://doi.org/10.2134/JEQ2010.0145

Ibrahim, M., Villanueva, C., Mora, J., 2005. Traditional and improved silvopastoral systems and their importance in sustainability of livestock farms. Silvopastoralism and sustainable land management. Proceedings of an international congress on silvopastoralism and sustainable management held in Lugo, Spain, April 2004 13–18. https://doi.org/10.1079/9781845930011.0013

López-Santiago, J.G., Casanova-Lugo, F., Villanueva-López, G., Díaz-Echeverría, V.F., Solorio-Sánchez, F.J., Martínez-Zurimendi, P., Aryal, D.R., Chay-Canul, A.J., 2019. Carbon storage in a silvopastoral system compared to that in a deciduous dry forest in Michoacán, Mexico. Agroforestry Systems 93, 199–211. https://doi.org/10.1007/S10457-018-0259-X/TABLES/3

López-Santiago, J.G., Villanueva-López, G., Casanova-Lugo, F., Martínez-Zurimendi, P., Jarquín-Sánchez, A., Bravo-Oviedo, F., Aryal, D.R., 2024. Carbon Reservoirs in the Biomass and Soil in Livestock Systems with Scattered Trees in Pastures in the Humid Tropics of Mexico. REVISTA TERRA LATINOAMERICANA 42. https://doi.org/10.28940/TERRA.V42I.1887

Mohammed, S., Naqvi, K., 2011. Global Climate Change: Role of Livestock. Asian Journal of Agricultural Sciences 19–25.

Nahed-Toral, J., Valdivieso-Pérez, A., Aguilar-Jiménez, R., Cámara-Cordova, J., Grande-Cano, D., 2013. Silvopastoral systems with traditional management in southeastern Mexico: a prototype of livestock agroforestry for cleaner production. J Clean Prod 57, 266–279. https://doi.org/10.1016/J.JCLEPRO.2013.06.020

Nair, P.K.R., 2012. Carbon sequestration studies in agroforestry systems: A reality-check. Agroforestry Systems 86, 243–253. https://doi.org/10.1007/S10457-011-9434-Z/METRICS

Rivera, J.E., Villegas, G.O., Serna, L.P., Chará, J., 2024. Cattle intensification based on silvopastoral systems with Leucaena leucocephala (Lam.) de Wit as a strategy to increase production and mitigate greenhouse gas emissions in the Caribbean region of Colombia. Agroforestry Systems 1–15. https://doi.org/10.1007/S10457-024-01000-Y/FIGURES/2

Singh, V., Rastogi, A., Nautiyal, N., Negi, V., 2017. Livestock and climate change: the key actors and the sufferers of global warming. Indian J Anim Sci 87, 11–20. https://doi.org/10.56093/IJANS.V87I1.66795

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. British Journal of Management 14, 207–222. https://doi.org/10.1111/1467-8551.00375

Yan, Z., Guo, Y., Sun, B., Gao, Z., Qin, P., Li, Y., Yue, W., Cui, H., 2024. Combating land degradation through human efforts: Ongoing challenges for sustainable development of global drylands. J Environ Manage 354, 120254. https://doi.org/10.1016/J.JENVMAN.2024.120254

Yusuf, R.O., Noor, Z.Z., Abba, A.H., Hassan, M.A.A., Din, M.F.M., 2012. Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. Renewable and Sustainable Energy Reviews 16, 5059–5070. https://doi.org/10.1016/J.RSER.2012.04.008

Zomer, R.J., Xu, J., Trabucco, A., 2022. Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. Scientific Data 2022 9:1 9, 1–15. https://doi.org/10.1038/s41597-022-01493-1