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Enhanced soil carbon storage in *Hylocereus spp.* systems: The role of cover crops

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ABSTRACT

This study quantified the impact of management practices on soil organic carbon (SOC) stock in *Hylocereus spp.* (dragon fruit) systems, contrasting alternative management (AM) using cover crops with conventional management (CM) of bare soil, in a subtropical environment prone to erosion. A total of 100 soil samples were collected from four depths (0–5, 5–10, 10–20, and 20–30 cm) across AM plots, CM plots, and an adjacent grassland (control) during the dry season of 2022. Statistical analysis revealed a significant difference ($p < 0.05$) in SOC stock between the systems, following the pattern: AM (47.01 t ha^{-1}) > grassland (45.77 t ha^{-1}) > CM (30.60 t ha^{-1}). The AM system, characterized by cover crops and minimal tillage, stored 16.41 t ha^{-1} more SOC on average than the conventional system. The CM system exhibited the lowest SOC concentration below the plant, likely due to intensive tillage and lack of cover. The implementation of cover crops and reduced tillage in dragon fruit production systems (AM) significantly enhances SOC storage, reaching levels comparable to natural grassland. These practices are important for developing sustainable dragon fruit farming, especially in high-erosion areas, serving as a powerful tool for climate change mitigation and soil health improvement.

Keywords: carbon sequestration, climate change mitigation, cover crops, *Hylocereus* spp., soil conservation, soil organic carbon stock.

INTRODUCTION

Global climate change is causing significant impacts, particularly in tropical and subtropical areas where agriculture is a central socioeconomic stake (Koudahe et al. 2022; Kim et al. 2020). In this context, soil health and its capacity as a carbon reservoir are highly dynamic, as the amount of Soil organic carbon (SOC) varies based on land-use activities (Haruna et al., 2020). The pursuit of climate change mitigation and agricultural sustainability demands the implementation of management techniques that reduce carbon emissions and promote sequestration, such as the use of cover crops and the optimization of fertilizers (Joshi et al. 2023). The increasing market demand is driving the rapid adoption of innovative crops, such as dragon fruit (*Hylocereus* spp.), which is increasingly replacing traditional staples in regions like Manabí, Ecuador. However, the expansion of dragon fruit farming often involves Conventional management (CM), which relies on extensive tillage and maintaining weed-free fields (Bowen and Meza, 2024). This practice leaves the soil surface exposed, impairing its ability to sequester organic carbon and raising concerns about long-term degradation due to erosion and compaction (Yousefi et al. 2024; Guillen et al. 2023). The cultivation sites in Manabí are frequently located on steep slopes (exceeding 30% gradient) with high, concentrated annual precipitation, which severely accelerates water erosion (Suárez et al., 2021). In contrast to the risks of

CM, the literature emphasizes the importance of Alternative management (AM) utilizing vegetative cover or cover crops. Vegetative cover improves soil quality, stability, biodiversity, and prevents degradation (Belbase et al., 2025; Belbase and Bhaskar, 2025). Beyond surface protection, this cover recycles nutrients, adds organic matter, and enhances the physical and chemical structure of the soil (Blanco-Canqui, 2022). Studies consistently indicate that practices that minimize soil disturbance (reduced tillage) and maximize cover crops promote increased microbial activity and, consequently, higher SOC stocks. Specifically, cover crops have been shown to increase soil carbon on average by 12% (1.11 Mg C/ha) (McClelland et al., 2021), contributing more aboveground and belowground residue biomass and significantly limiting SOC losses due to erosion. This protective and restorative role is decisive in perennial cropping systems like dragon fruit.

Despite the clear benefits of vegetative cover and the rapid increase in dragon fruit cultivation, there is a need to quantify the site-specific impact of these management systems on SOC stock, particularly under the challenging conditions of steep slopes and high erosion risk in Ecuador. The limited research available on *Hylocereus* spp. with differentiated management systems highlights a knowledge gap that requirements to be addressed.

Therefore, the purpose of this study was to quantify the effects of dragon fruit (*Hylocereus* spp.) production methods, contrasting AM with cover vegetation and CM without cover crops, on the SOC stock across different soil depths in the Manabí province, Ecuador. It was hypothesized that the implementation of alternative management practices, specifically the use of cover crops and minimal tillage, would result in significantly higher SOC stock throughout the soil profile compared to the conventional bare-soil management.

METHODOLOGY

Study area and site description

The study was conducted in a commercial dragon fruit (*Hylocereus* spp.) plantation located in the Manabí Province of Ecuador (Figure 1). The climate is classified as subtropical, with an average

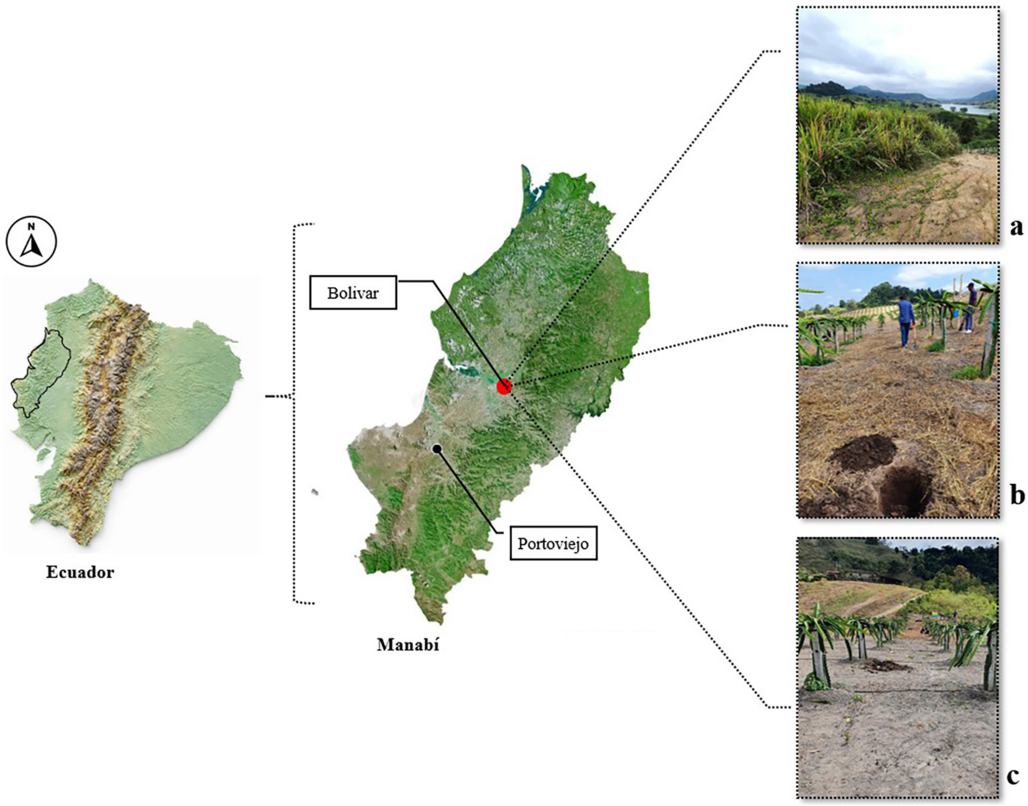

Figure 1. Study area in Finca Velásquez, in the province of Manabí Ecuador; (a) grassland, (b) soil with cover vegetation alternative management (AM) and (c) soil without cover crop conventional management (CM) both in the dragon fruit (*Hylocereus* spp.) plantation

annual temperature ranging from 24 to 26 °C and annual precipitation between 1000 and 1200 mm, primarily concentrated in a rainy season (December to May). The plantation was 1.5 years old at the time of sampling (July–August 2022).

The plantation is situated on steep slopes with gradients exceeding 30%, making the area highly susceptible to water erosion. The soil was provisionally classified as Fluvisols according to the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2022). Prior to the Hylocereus establishment, the land was utilized for natural grass and bush cover (control site).

Experimental design and treatments

The study employed a comparative design focusing on two primary, established management systems: AM and CM. An adjacent, undisturbed natural grassland was sampled as a reference (control) area for local soil conditions.

The AM system utilizes a minimal tillage approach to soil preparation, preserving existing vegetative cover which resulted in partial retention of herbaceous remnants within inter-row spaces. Weed control is achieved through an integrated strategy comprising a single annual application of a contact herbicide, supplemented by manual weeding at 4–5 month intervals. Pruning residue is managed via pit composting, with lime application for pH adjustment and potential pathogen suppression. Plant protection followed an integrated pest and disease management approach, utilizing both preventative and curative strategies based on continuous plant health monitoring. Fertilization involved edaphic application of both chemical and organic fertilizers, delivered manually. Fertigation (foliar, soil and drainage) was conducted at 30-day intervals, employing a combination of chemical and organic nutrient sources. Irrigation was localized using a drip system with emitters discharging 8 L/s, with two emitters per plant. CM cultivation consists of extensive tillage procedures, including plowing, which resulted in the entire elimination of existing vegetative cover and soil disturbance. Weed control required full vegetation clearance, including all plant remnants. Manual weeding was necessary at 30–45 day intervals during the dry season and 15–21 day intervals during the period of rainfall, indicating higher weed activity.

Soil sampling

Soil samples were collected during the dry season (July and August 2022). A total of 100 soil samples were collected, distributed as detailed in Figure 2: Management Plots (AM and CM): 80 samples were collected. Sampling locations within the plots were differentiated into five zones relative to the plant (Below Plant, Between Plants in the Row, Center of the Row, and the two respective transition zones—total 5 zones). Grassland Control: 20 samples were collected randomly from the adjacent undisturbed natural grassland area. Samples were collected at four depths in each location: 0–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm. For each sampling point, soil was collected using a core sampler of known volume. A portion of each undisturbed sample was immediately sealed in airtight containers to prevent moisture loss for subsequent gravimetric analysis, while the remaining soil was air-dried and sieved to 2 mm for laboratory analysis.

Soil analysis

The concentration of organic carbon (OC) was determined using the Walkley-Black

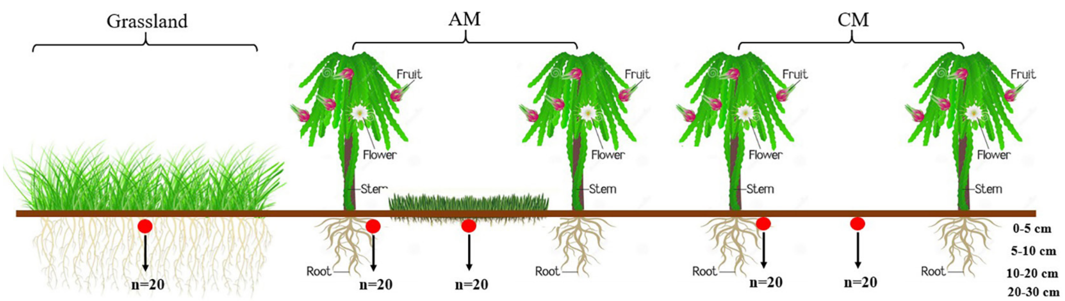

Figure 2. 100 soil samples (red points) were collected from under plants and in inter-row areas conventional management (CM) and alternative management (AM), at four depth intervals (0–5, 5–10, 10–20, and 20–30 cm). 20 additional samples were collected from grassland (control)

method (Walkley, 1947), which involves wet oxidation of the organic matter with potassium dichromate ($K_2CR_2O_7$) and titration with ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2$). The results were converted to OC concentration using the following equation:

$$OC\% = \frac{(V_b - V_S) \times M_{Fe^{2+}}\, x\, 0.003 \times f \times 100}{w} \quad (1)$$

where: V_b – volume of Fe^{2+} solution (mL) required for the blank sample titration, V_s – volume of Fe^{2+} solution (mL) required for the soil sample titration, $M_{Fe}{}^{2+}$ – molarity of the Fe^{2+} solution (mol/L), 0.003 – millimolar mass of carbon (g), f – correction factor (1.32), w – mass of the soil sample (g).

Bulk density (BD) (Mg/m^3) was determined using the core method, as described by (Blake and Hartge, 1986). Undisturbed soil cores were collected, dried in an oven at 105 °C until constant weight, and the mass was divided by the core volume. The volume fraction of coarse fragments (δ) was determined by separating and weighing the coarse fragments (> 2 mm) from the sieved soil samples and calculating their volume percentage relative to the total soil volume.

The soil organic carbon stock (SOC_{stock}) in tons per hectare ($t\ ha^{-1}$) for each soil layer was calculated using the following equation (Jobbágy and Jackson, 2000):

$$SOC_{stock} = OC \times BD \times d \times (1 - \delta) \quad (2)$$

where: OC – organic carbon concentration (%), BD – bulk density (Mg/m^3), d – thickness of the soil layer (cm), δ – volume fraction of coarse fragments, 10 – combined conversion factor.

Gravimetric soil moisture content (θ) was determined concurrently with bulk density using the thermogravimetric method (Black, 1965). The fresh soil weight was recorded immediately after sampling. Subsequently, the samples were oven-dried at 105 °C for 48 hours until a constant weight was reached. The moisture content was calculated as the difference between the weights of the wet and dry soil, expressed as a percentage of the dry soil mass ($g.g^{-1}$).

Statistical analysis

All data were subjected to a one-way analysis of variance (ANOVA) to determine significant differences in SOC stock, OC concentration, BD, and volume fraction among the three main land-use types (alternative management, conventional management, and grassland) and the four sampling depths. When the ANOVA indicated a statistically significant difference ($p < 0.05$), the Tukey's honest significant difference (HSD) post-hoc test was performed to compare means between the individual treatments and identify homogeneous groups. All statistical analyses were conducted using the R Statistical Software (version 4.2.2). Normality and homogeneity of variances were checked prior to analysis.

RESULTS

SOC concentration and accumulation

The analysis of total SOC across the 0–30 cm profile revealed significant differences influenced by the soil management practices. Both the AM system and the grassland control exhibited substantially higher mean SOC concentrations and total accumulation compared to CM system (Table 1).

The AM system recorded a mean SOC concentration of 4.60% and an SOC stock of 47.01 t ha^{-1}. While these numerical values were the highest observed, they were statistically comparable to those of the grassland (45.77 t ha^{-1}; $p > 0.05$). However, both AM and grassland exhibited significantly higher SOC stocks than the CM system (30.60 t ha^{-1}; $p < 0.05$).

Table 1. Mean organic carbon concentration (%) and organic carbon accumulation ($t\ ha^{-1}$) in different managements; grassland, AM and CM

System	n	Mean SOC concentration (%)	S.D.	Mean SOC stock ($t\ ha^{-1}$)	S.D.
Grassland	20	4.46	0.28 a	45.77	16.38 a
AM	40	4.6	0.48 a	47.01	17.11 a
CM	40	3.24	1.14 b	30.60	14.44 b

Note: Values in the same column followed by different letters (a, b) are significantly different ($p < 0.05$).

SOC concentration and stock distribution by depth

The distribution of SOC concentration and stock across the four soil depths (0–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm) revealed distinct management-dependent patterns (Figure 3). In the AM system, SOC concentrations remained highly consistent and statistically equivalent to the grassland control across all evaluated depths ($p > 0.05$). On the other hand, the CM system exhibited a significant depletion in SOC below the plant, reaching its lowest concentration at the 20–30 cm layer (1.78%, $p < 0.05$). While in-row SOC levels in the CM system were comparable to AM and grassland in the upper layers, a significant decline was observed at the deepest interval. Regarding SOC stocks, the integrated values across the 0–30 cm profile followed the pattern AM ≈ grassland > CM (Table 1), supporting the trend observed in surface concentration but accounting for soil bulk density variations.

Correlation and principal components analysis

The Pearson correlation analysis (Figure 4) highlighted varying relationships between variables based on the management system: AM and grassland systems showed a very strong positive correlation between soil depth and the

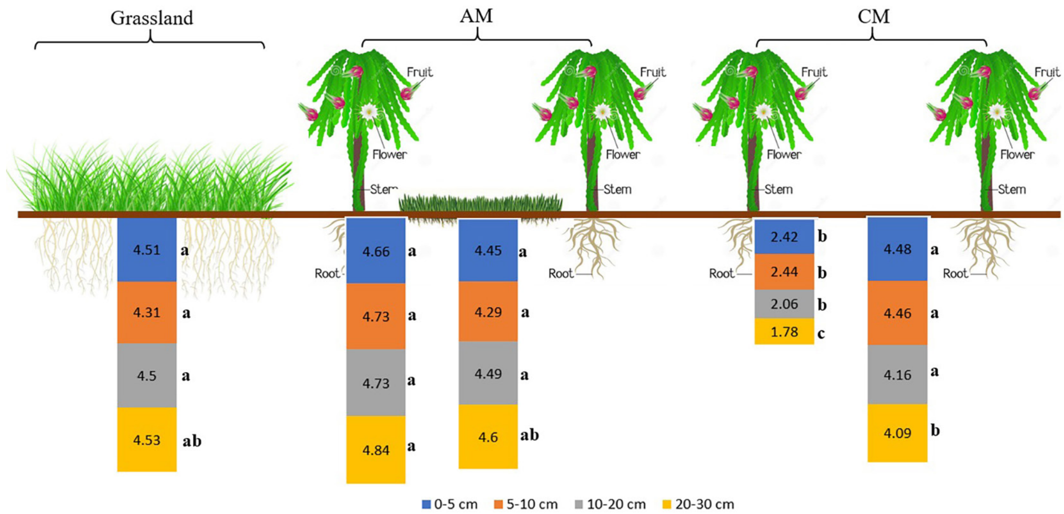

Figure 3. Depth profiles of SOC (%) in Grassland, soil with cover vegetation alternative management (AM), and soil without cover crop conventional management (CM), both in the Dragon fruit (*Hylocereus* spp.) plantation

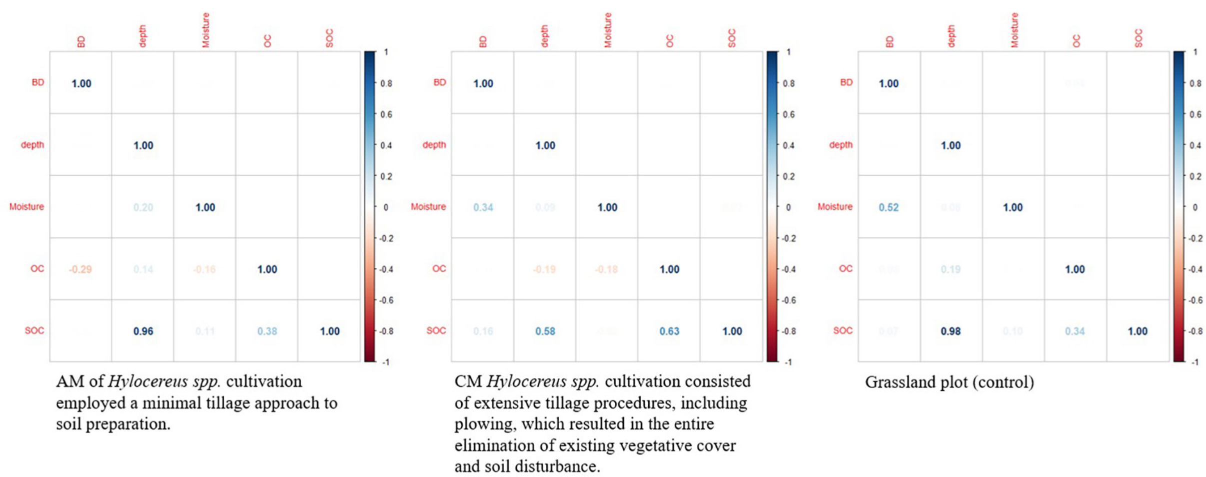

Figure 4. Pearson correlation in each of the soil management practices. Grassland, soil with cover vegetation alternative management (AM), and soil without cover crop conventional management (CM), both in the Dragon fruit (*Hylocereus* spp.) plantation

accumulation of organic carbon (0.96 and 0.98, respectively), indicating efficient C incorporation throughout the soil profile. Grassland exhibited a stronger correlation between Bulk density (BD) and soil moisture (0.52) compared to the other treatments. In CM, the correlation between soil depth and SOC was lower (0.58). However, the correlation between SOC concentration and accumulation was higher, suggesting a superficial enrichment that may not be sustainable.

The principal component analysis (PCA) (Figure 5) confirmed the above described relationships. The grassland and AM treatments (beneath the plant and in the rows) clustered together and were strongly associated with the vectors for OC and SOC. This indicates that vegetative cover promotes carbon accumulation and storage. The CM treatments clustered separately, primarily associated with the soil moisture vector, suggesting that exposed soil conditions lead to rapid moisture fluctuations and negative effects on physical properties.

DISCUSSION

The results demonstrate that AM practices, incorporating cover crops, are significantly more effective at preserving and enhancing SOC stocks in *Hylocereus* spp. plantations compared to CM. The observed pattern (AM ≈ grassland > CM) supports the hypothesis that sustainable management can restore soil carbon to levels comparable to undisturbed systems. These findings align with numerous studies worldwide that emphasize the importance of managing the topsoil layer for SOC buildup (Maris et al., 2021; Rocco et al., 2024; Yousefi et al., 2024) highlight that minimizing soil disturbance through reduced tillage and maximizing soil cover are crucial practices that enhance microbial activity, organic matter decomposition, and structure, thereby maximizing organic carbon sequestration.

The most significant contribution of this study is the rapid recovery of SOC under AM, reaching a stock of 47.01 t ha^{-1} in just 1.5 years, a value statistically equivalent to the natural grassland control (45.77 t ha^{-1}). This indicates that the high-biomass, subtropical AM system is efficient, yielding a difference of 16.41 t ha^{-1} over the CM system. This gap is attributed to the protective role of cover crops, which mitigate the erosion and carbon mineralization typically found in bare-soil CM systems. While other authors, such as (McClelland et al., 2021) noted a global average increase of 12% (1.11 Mg C/ha) with cover crops, the sequestration efficiency found in this high-biomass, subtropical AM system appears to be exceptionally high. This large difference is attributed to the fact that CM leaves a substantial area of the soil surface bare of vegetation.

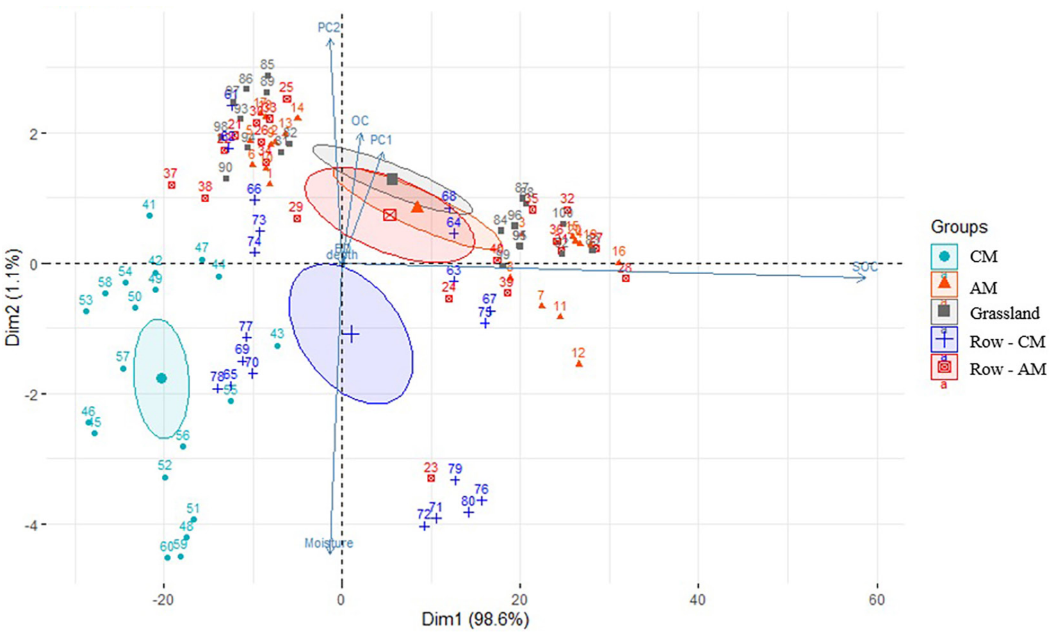

Figure 5. Principal component analysis (PCA) with Biplot grouped into different soil management practices. Grassland, soil with cover vegetation alternative management (AM), and soil without cover crop conventional management (CM), (grass, under plant, row) both in the dragon fruit (*Hylocereus* spp.) plantation

(Huerta-Olague et al., 2018) discovered a negative exponential connection between vegetative covering and soil loss, underlining the superior buffering capacity of plant cover against erosive agents compared to bare soil.

The SOC stock in CM plots (30.60 t ha^{-1}) is particularly low. This lines up with (Liu et al., 2023), who pointed out that some agricultural practices, such as those used in dragon fruit production, may be less successful in preserving SOC than other land uses. The high SOC stocks in the AM system are primarily attributed to the continuous input of organic matter from the cover crops. (Haruna et al., 2020; Kim et al., 2020) confirmed that cover crops provide increased aboveground and belowground crop residual carbon, which is incorporated into the soil matrix. (Koudahe et al., 2022) specifically highlighted the importance of integrating cover crops within perennial systems, as they supply organic matter through root biomass and residue breakdown, supporting a healthy microbial community and increasing the SOC stock (Kim et al., 2020). Furthermore, (Breil et al., 2023) stated the role of cover crops in significantly limiting SOC losses due to erosion, a critical factor on the steep slopes of our study site.

The most striking result is the low SOC found in the CM system's below-plant region (1.78% at 20–30 cm, Figure 3). This underscores the necessity of focused approaches for carbon retention. This reduction can be explained by the application of chemical fertilizers on the soil surface under CM. While this raises the concentration of organic carbon in the uppermost layer, the correlation analysis suggests this accumulation may not be stable or derived from natural sequestration. Instead, the lack of cover combined with the effects of tillage accelerates the mineralization and oxidation of native SOC, leading to significant losses (Lal, 2020). The correlation analysis further supports this, showing that CM is associated with bare, highly exposed soil, which has negative impacts on physical and chemical properties, while AM (like the grassland control) promotes carbon accumulation throughout the soil profile via living or dead vegetation cover (Poeplau, 2021).

CONCLUSIONS

The study confirms that the production system strongly influences SOC stocks in young *Hylocereus* spp. plantations. The AM system, utilizing cover crops, achieved SOC levels equivalent to those of natural grassland, resulting in an increase of 16.41 t ha^{-1} compared to the CM system. The overall SOC stock followed the pattern AM ≈ grassland > CM, proving that alternative management effectively halts the degradation observed in conventional systems. While AM maintained high and consistent SOC concentrations across the 0–30 cm profile, the CM system showed a degradation zone below the plant, with concentrations as low as 1.78%. These findings identify cover crops as a suitable strategy for the rapid restoration of soil health and the enhancement of carbon sequestration in high-risk, steep-slope dragon fruit agroecosystems. By significantly accelerating SOC buildup, the AM approach facilitates the transition toward a more resilient and sustainable agricultural model, essential for climate change mitigation in subtropical perennial crops.

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