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Contribution of pecan (*Carya illinoinensis [*Wangenh.| K. Koch) to Sustainable Development Goal 2 under the dual perspective of carbon storage and human nutrition

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This work aims to contextualize and analyze the potential contribution of pecan to SDG2 under the dual perspective of carbon storage and human nutrition. Particularly, the study focuses on the pecan agroecosystems in the Americas, representing the most important pecan-producing countries (the United States, Mexico, Brazil, Argentina, Uruguay, and Peru). We observed that pecan is a reliable sink for storing atmospheric C and also for quality nuts with high nutritional density. The Americas, hold a population of ca. 23 M pecan trees, with the younger tree populations and the highest C-storing potential in South America. This pecan tree population has removed 51.3 Mt CO2eq immobilizing the OC in their aboveground biomass, but if the C sequestration for the whole system is considered, the value reaches nearly 80 Mt CO2eq. From a nutritional perspective, there are different dietary needs to cover according to the country, although the common analysis output is a low proportion of nuts in the diet, which is expected to improve, given the efforts of each country to promote domestic consumption. All the mentioned countries in this study have a low pecan consumption going from 8 to 293 g per capita yr^{-1}, which in the light of the Global Burden of Disease represents 0.08 to 3.2% of the recommended yearly dietary basis for nuts overall. The inclusion of pecan nuts in the daily diet is of utmost importance to offset the food nutrient dilution carbohydrates-based, linked to the excess of atmospheric CO$_2$. Also, pecan orchards function as a platform to integrate sustainable systems. The global benefit of having pecan and alley crops has been proved in regions other than the Americas with interesting economic outputs leading to energizing the life of rural communities. Pecan orchards and pecan agroforestry may lead to sustainable agri-food systems, with global gains in SOC and nutritional richness and diversity. Therefore, more in-depth studies are needed not only to fully understand the functioning of the systems at a productive level but also to design and plan sustainable landscapes in rural land.

KEYWORDS

pecan (*Carya illinoensis*), soil organic carbon, nutrition - topics, GHG emission, sustainability

1 Introduction

Current ways of field engineering and management of agri-food systems (AFSs) are increasingly undermining environmental sustainability and human health through two main negative impacts: (a) the soil organic carbon (SOC) depletion–greenhouse gas (GHG) emission process (1) and (b) the poor-quality diet–based global nourishment. Many initiatives with worldwide—as well as regional—reach are addressing these impacts through the point of view of, for example, practices leading to soil carbon (C) enrichment; such is the case for the "Four per Thousand" initiative (2, 3). Unlike this soil and agricultural standalone perspective, the framework of the UN Sustainable Development Goals (SDGs) approaches the problem from a more holistic, integrated point of view, aiming for AFSs with less GHG emissions and a global population with a more balanced, healthy diet (4). Among the SDGs, SDG 2 ("Zero Hunger") is the one straightforwardly linking sustainable agriculture to nutrition, recognizing the strong bond between environmental sustainability and human health (4, 5). This bond can be visualized in targets 2.2 and 2.4, where SDG 2 suggests to "…end all forms of malnutrition…" and "…ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters, and that progressively improve land and soil quality…." To reach those targets by 2030, the contributions of AFSs yielding edible products are essential.

The focus on edible crops as contributors to SDG 2 is of growing importance, even more so knowing that a continuous decline in the nutrient density of produce for the USA and UK has been revealed since ca. 1940, with iron (Fe), zinc (Zn), phosphorus (P), and sulfur (S) concentrations being significantly diluted in edible fruits (6). The latter can be considered a representative trend since the author (6) analyzed and compared the data of several studies, nutrient concentration–related for edible fruits, concluding that the change for more yielding varieties explained this dilution. Nonetheless, to attribute nutrient dilution in edibles only to genetic improvement means to overlook other problems. On one hand, continuous agriculture has been inducing not only SOC stock depletion through C mineralization and respiration but also soil nutrient depletion, mainly in those areas where SOC stock in the top 100 cm layer concentrates only 50–100 t C ha^{-1} and agricultural systems have not adopted neither soil conservation practices (1, 7) nor soil nutrient replacement through soil fertilization. On the other hand, the atmospheric CO_2 increase may have also contributed to this process (8): in a recent study, Chen et al. (9) revealed that atmospheric CO_2 increase induced a mean annual gain in global primary productivity of 44 kg C ha^{-1} year^{-1} since the 2000s, contributing to the dilution of nutrients contained in food. Furthermore, Myers et al. (10) reported that, under an environment concentrating 550 ppm CO_2, a 5%–10% decrease in mineral content is produced for cereal grains and legumes (the vitamin B group, iron, zinc, and sulfur are affected). Therefore, this is why the dynamics of carbon storage (either in soil or in plant biomass) and human nutrition are so intrinsically linked, making the systems with dual contributions (carbon sequestration in soil and plant biomass and the provision of high nutrient density—food) a key toward the achievement of SDG 2 by 2030.

Few food systems have this inherent duality of increasing carbon storage in the environment through C sequestration and providing nutrient-dense food, being the dried fruit-based systems important contributors to this matter (11). Pecan (*Carya illinoinensis* [Wangenh.| K. Koch) production is among these systems and has this duality enhanced because it not only produces a high-quality nut but also sequesters C in its biomass (mainly in the trunk) and the soil, given its strong association with ectomycorrhizal fungi (12). Many research efforts currently concentrate on pecan, and this growing interest is reflected in the publishing trend of the last decades, where studies about pecan have skyrocketed. For example, the ScienceDirect page shows that the annual publishing of pecan-related articles went from 83 to 423 during the period 2000–2021, with 58% of the articles produced between 2013 and 2021. Additionally, the browser Scopus showed a similar trend but refined the search (Figure 1A). Considering the same period, articles were labeled as belonging to "Agricultural and Biological Sciences," "Environmental Science," "Medicine and Dentistry," or "Immunology and Microbiology" (Figure 1B). Additionally, if performed in Google Scholar, the search with the keyword "pecan" casts the raw number of 9,230 articles only for the period 2020–2021, without excluding languages other than English. Those results are no minor data since pecan is ranked sixth among the main nuts globally produced (3% of the global nut production), with an annual increase of production of 4.74 t (13). Furthermore, the global area planted with pecan represents 4% (ca. 410,000 ha) of the total area planted with nuts (14). Despite the mentioned importance of this edible crop, no assessment up to date has analyzed pecan contributions to SDG 2, targeting its capacity to build climate resilience and improve the human diet.

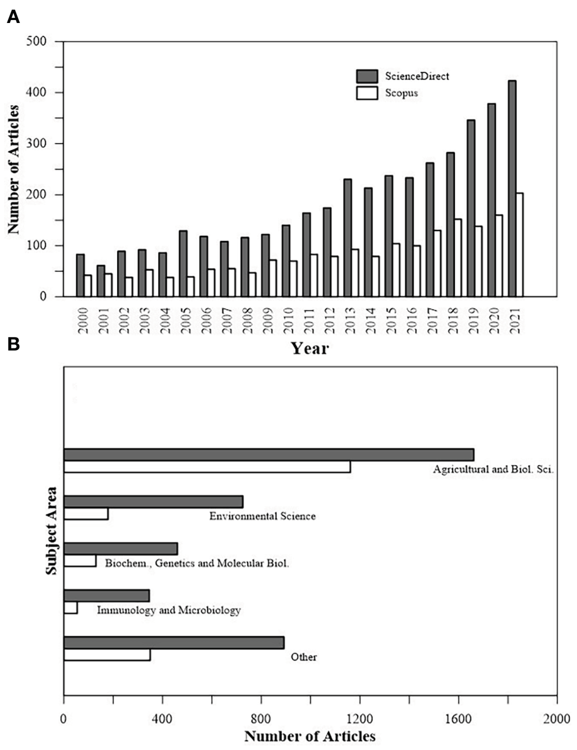

FIGURE 1
Published articles related to pecan during the period 2000–2021. **(A)** According to year and scientific browser. **(B)** According to subject area and scientific browser.

The conceptual framework for our analysis is shown in Figure 2, where C enters the pecan agroecosystem through C fixation; is sequestered in tree biomass; and eventually moves through several compartments such as leaves, husks, and pruning residues until is harvested along with other nutrients. We also considered that C sequestered in leaves, pruning residues, and other debris effectively contributes to build the SOC pool since ectomycorrhizal fungi win the competition for water against decomposer *fungi*, and the latter cannot rapidly decompose carbonated chains (15).

Few studies have analyzed what happens with C under a pecan orchard (16–18), although from a single point of view. An interesting contribution is that of Lee and Jose (17), which evaluated how soil respiration and C stock responded to pecan orchard aging, with the older pecan orchard having not only greater CO_2 emissions but also greater SOM, microbial biomass, and fine root biomass than the younger orchard. Hence, the integration of these three approaches, C fixation (16), C balance (18), and soil C respiration and microbial biomass (17), gives an idea of the building of not only climatic resilience with pecan but also a proper "muscle" plant architecture to extract nutrients and turn them into a nutrient-dense edible product. Thus, a standalone, partial perspective could not wholly address any contribution to SDG 2 by pecan.

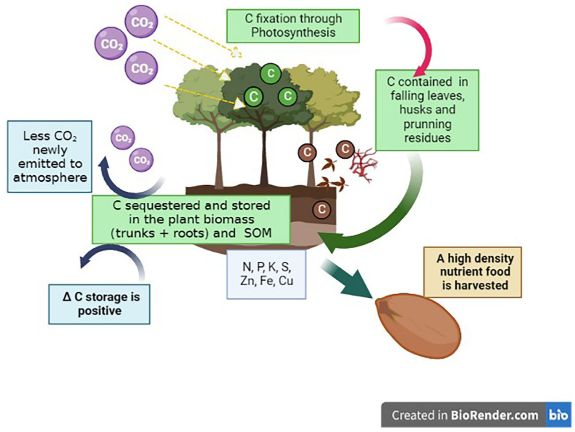

FIGURE 2
Carbon recycling through the pecan agroecosystem and its two main results: positive C balance (Δ C storage) and high-density nutrient food. Diagram created in Biorender.com (2022).

1.1 Methodology for literature screening

To properly conduct a review of this kind, we refined our search in ScienceDirect, Scopus, Google Scholar, and other additional scientific browsers in order to build a sufficiently strong literature database of long-term and short-term field research, meta-analyses published in peer-reviewed journals by introducing the terms "pecan," "nuts," "noz pecá," "nogales," "nuez pecanera," "orchard," "carbon dioxide," "carbon sequestration," and "nutritional quality." We also related the aspects of this search with regional information such as maps and statistics.

1.2 Objectives

Unlike previous research efforts focused on analyzing standalone components of the pecan production system, this review adopts a novel perspective to contextualize and analyze the potential contribution of pecan to SDG 2 under the dual perspective of carbon storage and human nutrition. Particularly, the study focuses on the pecan agroecosystems in the Americas, considering the most important pecan-producing countries (the USA, Mexico, Brazil, Argentina, Uruguay, and Peru). Therefore, the American pecans are here understood as an AFS that may potentially provide several opportunities to meet SDG 2's 2.2 and 2.4 targets. Our review is particularly relevant as the value of pecans is often measured only based on their economic and social benefits, while their function and current and potential role in climate change mitigation has been systematically overlooked.

The rest of this paper is structured as follows. Section 2 summarizes the literature on the problem of soil carbon depletion in AFSs and the role of pecan-based agroforestry as an SOC improver. Section 3 demonstrates the global need for a balanced diet and the nutritional value of pecan. Section 4 mainly exposes relevant statistics about pecan production and planted area in the Americas, with estimates about carbon stock. Section 5 puts forward the relevance of pecan orchards as a platform to integrate sustainable AFSs. Section 6 analyzes pecan orchards as a sink for carbon sequestration in aboveground and belowground biomass. Finally, Section 7 bears conclusions and recommendations.

2 The challenge of soil organic carbon depletion in agricultural food systems and the role of pecan-based agroforestry as a soil organic carbon improver

In the previous paragraphs, we introduced some of the SOC depletion problems from the point of view of the AFSs overall, highlighting some advantages of the pecan AFS to store C. To fully grasp the contribution of pecan to carbonize the AFS through C storage and sequestration, we will focus on two C loss paths: soil GHG emissions and soil erosion. We will also remark on the role of pecan orchards and pecan-based agroforestry.

2.1 Soil organic carbon loss and soil greenhouse gas emissions vs. carbon sequestration

The Agriculture, Forestry, and Other Land Use activities contributed to 13% of CO_2, 44% of CH_4, and 81% of N_2O emissions from human activities during 2007–2016 (19); however, depending on the soil management and land use, agricultural activities can be considered as a source or sink of GHGs, changing the carbon and nitrogen dynamics (19, 20) and contributing negatively or positively to the global C budget. For example, Sanderman et al. (21) estimated that, at the global level, soils accumulated a C loss of 116 Pg at 2 m depth. This loss is often associated to regions with soil degradation caused by crop and pasture mismanagement, leading to high soil respiration rates and SOC exhaustion, suggesting that these regions should be targeted in efforts to restore SOC (21). The global estimates of total degraded areas range from 1 to 6 billion ha, which represents 40% of the world's soil (22, 23). Planting pecan orchards can contribute to mitigate SOC loss in such areas by acting over soil C respiration (15, 17) and through C sequestration (16).

Carbon sequestration (as in soil as well as in trees biomass) can significantly contribute to the stabilization of global warming levels, helping to keep the annual global temperature increases below 2°C or even 1.5°C in relation to pre-industrial levels, a target stipulated in the Paris Agreement (21st Session of the Conference of the Parties or COP-21) (23, 24). In such a sense, it has been estimated that an annual 0.4% increase in the SOC stock of the 0–40 cm layer of the soil can offset anthropogenic emissions and stabilize climate change, in addition to ensuring food security (3). Nonetheless, the latter estimate overlooked the contribution of C sequestered by tree trunks.

Likewise, although some conservationist agricultural practices (e.g., no till) to protect the soil and increase SOC are essential for maintaining the sustainability of agricultural systems and the environment (25–27), they demand more inputs every year. Therefore, the adoption of agricultural systems based purely on low-carbon agriculture technologies is a condition *sine qua non* to guarantee a positive C budget. Agroforestry plays a significant role to guarantee that result, with South America having a high potential to offset global emissions, estimated approximately 8.24 Pg C for the period 2016–2050 (28). As mentioned earlier, and given its suitability for agroforestry, pecans perfectly fit to meet this challenge. Thus, the assessment of the environmental impacts caused by agricultural systems has increasing focus, as well as the development of technologies and agricultural management practices to reduce and offset these impacts (29, 30). Agricultural management practices can significantly change the dynamics of GHG emission; thus, it is essential to study and monitor GHG fluxes in different climate and soil conditions (31–33).

Agroforestry systems seek sustainable agricultural production by associating the different agricultural, livestock, and forestry production systems, which can be done in intercropping, in succession, or in rotation, mutually benefiting the components (34, 35). The adoption of less aggressive management practices, such as the agroforestry system replacing the conventional system of cultivation, contributes to the mitigation of CO_2 and stores greater amounts of C in the soil (36–38). That system increases the plant residues in the soil surface and the soil organic matter content, reducing soil erosion and improving their resilience and their capacity to store carbon (34, 39). For example, after 4 years of conversion of degraded pasture to an agrosilvopastoral system in Brazil, there was an increase in soil organic carbon stocks from 52.6 to 66.5 Mg ha^{-1}, indicating that it is a sustainable alternative and option for the recovery of degraded soils (37). In addition to the recovery of degraded areas, the agrosilvopastoral system preserves forest areas due to the land spare effect and brings economic and social impacts, promoting positive effects throughout society (40, 41). Similarly, a nut tree–based agroforestry can lead to counterbalance SOC loss and soil GHG emissions through C sequestration (11).

2.2 Soil organic carbon lost by soil erosion as mitigated by cover crops in pecan-based agroforestry

Soil C erosion is driven by a weakened soil structure as result of poor agricultural practices applied in susceptible soils, which impacts long-term soil sustainability (21, 27). This loss of C also reflects the exhaustion of other nutrients as it has been demonstrated in the Argentina`s case (42). Alike the soil GHG emissions problem, several farming practices have been identified to minimize or restore SOC loss by reducing soil erosion and improving soil quality (43). One of the most widespread practices is the use of cover crops, which have been demonstrated to enhance SOC sequestration when applied to pecan-based agroforestry systems (44).

Overall, soil C sequestration depends upon the weather (especially temperature and rainfall) and soil characteristics (45) that affect the activity of the soil microorganisms involved in degrading organic residues (46) and the amount and quality of the

C input (47). For that, indicators such as the precipitation/temperature ratio are essential for understanding cover crop residue decomposition in different environments (48). In addition, soil texture is another key factor that may modify soil C fixation (49) by regulating soil aeration and, consequently, SOM decomposition and mineralization (27). In fine-textured soils, the smaller average pore size and the presence of organic–mineral complexes reduce SOM exposure to microbes for mineralization compared with the large pore sizes typical of coarse-textured soils (50). Thus, cover crop residues decompose differently according to the location and the system they are included in. For example, the inclusion of cover crops in cropping systems showed average SOC sequestration rates of 0.45 t C ha^{-1} yr^{-1} in the Pampa Region (51–53), fertilizer use (urea, 46% N) showed an increment of approximately 0.18 t C ha yr^{-1} (54, 55), and the inclusion of cycles with perennial pastures in crop rotations showed average SOC sequestration rates of 0.76 t C $ha^{-1}yr^{-1}$ (56, 57). Then, with proper management, a cover crop growing upon a pecan-based agroforestry system may boost soil C sequestration, adding up to soil biomass produced by the association between pecan and ectomycorrhizal fungus (15).

It worth mentioning that current area meant for agroforestry could sequester up to 2.2 Pg C above- and belowground in the next 50 years, but estimations on the global land area occupied by agroforestry systems are particularly uncertain. Global areas under tree intercropping, multistrata systems, protective systems, silvopasture, and tree woodlots are estimated at 700, 100, 300, 450, and 50 M ha, respectively. The SOC storage in agroforestry systems is also uncertain and may amount to up to 300 Mg C ha^{-1} to 1 m depth (58). In China, for example, a meta-analysis provided evidence that existing agroforestry systems, particularly shelterbelts and agrosilvicultural systems, increase SOC stocks due to not only SOC sequestration but also the effect of protection against wind and water C dispersal. Moreover, Mayer et al. (59) observed that the use of agroforestry systems increases SOC compared to cropping systems in a temperate climate. In either case, pecan-based agroforestry integrated in the green belts of the cities may bring substantial benefits by increasing and conserving SOC stocks.

2.3 Pecan orchards, pecan-based agroforestry, and their role as a soil organic carbon improver

Under the context described above, pecan orchards and pecan-based agroforestry have interesting implications on soil health and particularly on SOC. In such a sense, pecan trees growing in their native region (the USA and Mexico) will successfully prevail in well-drained, OM-rich soils, which, in addition to being subjected to C enrichment *via* the shedding of pecan leaves, shucks, sticks, bark, and other debris, self-generate high-quality conditions (60). In a well-detailed study performed during 2020 and 2021, Slade and Wells (61) found that the values of active carbon, aggregate stability, organic matter, total N, and Solvita CO_2-burst (a test for measuring soil microbiological activity) for different aged pecan orchards amply overpassed those of row crops, with the most aged orchards having better soil quality. In another study, Dold et al. (44) marked the relevance of the contribution of the leafy material to carbon sequestration and N supply to soil in a 17-year-old pecan-based agroforestry system, estimating a mean contribution of 17 and 0.68 kg N $tree^{-1}$ for falling pecan leaves during 2016. Finally, Idowu et al. (62) proved that the addition of pecan husks to arid soils boosted P, K, and wet aggregate stability for sandy clay and sandy loam textured soils. Therefore, this positive feedback between what is produced aboveground and the soil ensures soil with high standards of quality, offering a unique AFS to cope with soil C emissions and soil erosion. Moreover, soil quality is intrinsically associated with food quality and with the agricultural practices leading to maintain such quality. In that sense, after evaluating the effects of conventional and organic fertilization on pecan, Noperi-Mosqueda et al. (63) concluded that the nutritional properties of the pecan nut were improved under a balanced combination of both fertilization practices, with phenolic compounds N, P, and K being in the highest values. In addition, falling pecan husks have been proven to absorb heavy metals like chromium (64); thus, food produced under this type of agroecosystem can be considered environmentally safer than other AFSs.

In future studies, effort should be put on understanding the response of the biophysics (soil temperature, soil moisture, etc.) to management in the pecan orchard when integrated to agroforestry, in order to develop robust models to predict C cycling in these systems.

3 The global need for a balanced diet and the nutritional value of pecan

Food production is scarce to cover the needs of the world's population, but there are also serious drawbacks in its distribution and unacceptable loss and waste that call for a profound and detailed reconsideration of the actual food system (4). While a big part of the world's population is suffering from undernourishment, the percentage of people affected by overweight, obesity, and other non-transmissible diseases that are directly conditioned by the diet keeps growing. Efforts done by doctors, researchers, health organizations, and others have made it possible to accumulate much knowledge about the needs for a healthy life. Numerous balanced diets and food intake recommendations are spread around the world. Nevertheless, average consumption varies vastly from country to country, from region to region, being in many places far from the suggested healthier values. It is painful and embarrassing for humanity that 1,562 persons are facing starvation and death daily because of not accessing the food they need (65).

Average dry fruit consumption in the world appears to be among the lowest values compared with those of other food groups (4). The importance of consuming dry fruits and nuts, including pecans, has been determined in many studies, and there are different efforts to promote their consumption considering the benefits they generate (66). The nutritional composition of pecan nuts (Table 1) varies from cultivar to cultivar (67–73), and, most likely, the growing site conditions influence this composition. In average, 100 g of pecan nuts contain 69.3 g of oil, and significant concentrations of micronutrients (K, P, and Mg) and antioxidants (phenols, tannins, and tocopherols) (Table 1). In any case, the inputs accounted for in our diets from pecan consumption will be highly beneficial.

Antioxidant potential due to the high content of phenols has been determined and puts pecan among the highest when compared to the rest of the food sources (74, 75). The nutraceutical compounds present and the fatty acid profile of pecan oil (76) make it possible to classify it as one of the healthier oils together with olive oil.

Studies carried out by numerous researchers prove the beneficial effect of consuming pecan due to increased blood circulation and the reduction of cardiovascular diseases (77, 78), reduced risks of type 2 diabetes (79), a positive influence on the development of the immune response, and the alleviation of inflammatory processes (74).

A recent review by Naghshi et al. (80) looked at the association between nut consumption and the risk of having cancer and its mortality. The meta-analysis carried out over 52 published papers led them to conclude that a 5 g day^{-1} increase in total nut intake can be associated to 3% and 25% lower risks of overall and colon cancers occurrence respectively, values that increased with higher nut intakes. Moreover, regarding cancer mortality, the authors found a 4% lower risk of cancer mortality with the 5 g day^{-1} total nut intake.

The consumption promotion of nuts has also developed the interest to determine if there is a health issue to be considered in regard to the negative effects that could be caused by too high an intake. As an example, some studies have considered the potential of reaching harmful levels of heavy metals (81), but no special consideration arises under normal production and consumption conditions.

Although there is enough information to support all the measures toward the increase of pecan production and consumption, more studies and analyses linking nutritional and environmental aspects are needed for pecan.

4 Pecan-planted area and production in the Americas

Although the pecan-planted area is concentrated around its origin region of origin (the USA and Mexico altogether contribute 76.2% of the planted area worldwide), the species is making progress in other regions of the world as seen in Table 2. These statistics about the planted area show not only pecan's distribution worldwide but also its capability to adapt to a diversity of soils and environments, which is especially notorious in the American continent, the focus of this analysis. The following two sections characterize pecan production in North and South America.

4.1 Pecans in North America: Contribution of pecan to carbon stocks and daily diet

4.1.1 Pecans in the USA

Pecan nut production in the USA is concentrated in the states of Georgia (55,870 ha), Texas (44,534 ha), Oklahoma (38,057 ha), New Mexico (18,623 ha), and Arizona (8,907 ha), with 40.3, 16.3, 5.1, 35.8, and 18.6 kt of nut harvested during 2021, respectively (82). The historical particularities of pecan distribution in the USA were well noted by Hall (83) who tracked the location of native and improved varieties of pecan (Figure 2). According to the latter assessment and the Global Soil Organic Carbon Map (84), pecans located in the two most planted states have a significant role in keeping carbon accounts beneficial for the environment since the soils beneath them are not well provided of C (Figure 2), if compared to other regions. For example, in Georgia, pecans are planted in a zone where SOC is 10–20 t ha^{-1} in the top 30 cm soil layer (Figure 3A), while, in Texas, they are planted at soils with 20–60 t C ha^{-1} in the same soil layer (Figure 3B); however, as the orchards age, their benefits grow more tangible, with the fine root

TABLE 1 Nutritional composition of the pecan kernel at 4% humidity.

Macromolecules (% of kernel)							
Oil	Protein	Phenols		Carbohydrates^{2}		Ash	
69.28 ± 0.43[1]	6.82 ± 0.37	2.78 ± 0,22		15.40 ± 0.61		1.71± 0.05	
Mineral composition (mg 100 g $^{-1}$)							
K	P	Mg	Ca	Mn	Zn	Fe	Cu
422.65 ± 27.91	365.38 ± 32.79	166.02 ± 12.34	72.40 ± 6.14	5.05 ± 0.58	4.62 ± 0.46	1.52 ± 0.16	0.97 ± 0.08
Antioxidants							
Phenols^{A}		Tannins^{B}		γ-Tocopherol^{C}		β-Tocopherol^{C}	
27.71 ± 2.13		6.94 ± 0.89		115.33 ± 5.48		18.63 ± 1.29	

[1] Mean ± standard error of mean.

[2] Carbohydrate content estimated as the difference between 100% and the sum of other components analyzed.

^{A}Phenols: Total extractable phenolic compounds as mg GAE·g^{-1} kernel; ^{B} Tannins: Condensed tannins as mg CE·g^{-1} kernel; ^{C} g and β-tocopherol as mg of α-tocopherol·g^{-1} kernel
Adapted from Ferrari et al. (67).

TABLE 2 Pecan planted area by region and country.

Region	Country	Planted Area (ha)
North America	*USA*	165,992
	Mexico	144,649
	Subtotal	***310,641***
South America	Brasil	12,000
	Argentina	8,000
	Peru	2,950
	Uruguay	1,000
	Subtotal	**23,950**
Africa	South Africa	38,800
Asia	China	34,000
Oceania	Australia	1,400
	Total	**408,791**

mass supplying more C to the soil as noted by Lee and Jose (17). Additionally, the importance of roots as providers of C-derived energy for shoot growth must also be remarked since their role is crucial to designing best management practices to mitigate the effects of alternate bearing on nut yield (85). Associated to this alternate bearing is the husk production pulse, which may influence C return to the soil every year since husks are rich in carbohydrates and fiber (64).

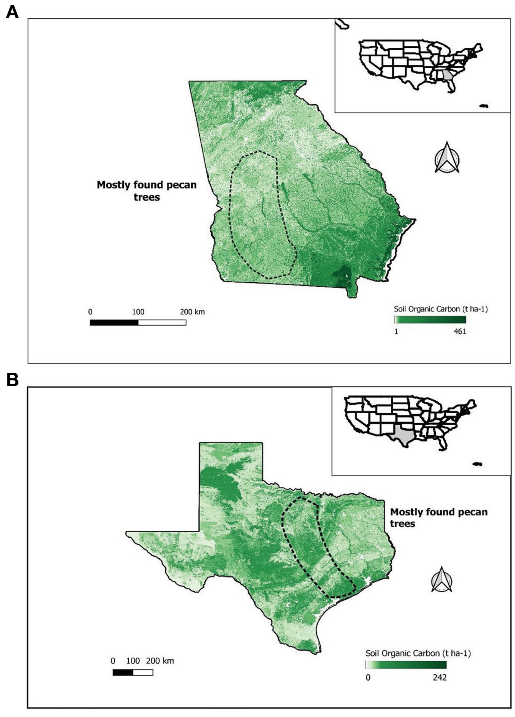

FIGURE 3
Soil organic carbon (SOC) and pecan's most frequently planted area according to Hall (83) for **(A)** Georgia and **(B)** Texas states. Source: own elaboration in QGis v. 3.26.2 (2022) based on the Global Soil Carbon Map (84). The map in the upper right indicates the location of the states in the USA.

The previously mentioned cycling is weak in newly planted orchards but grows stronger as the orchard ages and eventually interrupted when the orchard is put off production. Consequently, abandoned and newly planted orchards are relevant to build a C stock inventory since most of sequestered C is in the plant biomass. According to Wells (86), between 2010 and 2014, 391,448 pecan trees were planted in Georgia, which, to date, means a pool of 8- to 12-year-old trees storing 5.6–23.1 kt C aboveground if we consider an annual trunk diameter growth of 12 mm and an exponential relationship between trunk diameter and aboveground biomass (87, 88). A gross 18% of that aboveground C (16) is associated with nut production (including nutshells) and necessary to densify the essential nutrients into the nut kernel. Those depositions may also offset methane and nitrous oxide emissions that occur after irrigation (89).

From a nutritional perspective, the entering of new orchards into production satisfies an increasing demand and interest of consumers for pecans. On a kernel basis, the USA produces nearly 60 kt of nuts every year, out of which 41% are for export and the rest covers an annual consumption of 293 g *per capita* (13) if the total population is considered. This *per capita* annual consumption is closer to that suggested by Food and Agriculture Organization of the United Nations (FAO) (90) for nuts overall (2.13 kg per capita) than the current global consumption of pecan (34 g per capita) (13). However, under the parameters of the last Global Burden of Disease, a healthy diet must include 25 g of either nut in the per capita dietary daily intake (9.12 kg on an annual basis), which would reduce global CO_2 emissions between 3.8% and 23.1% compared to 2010, contributing significantly toward achieving SDG 2 (4).

4.1.2 Pecans in Mexico

In Mexico, pecan production is centralized in the north of the country, being the states of Chihuauhua (89,188 ha), Coahuila (20,880 ha), Sonora (19,536 ha), Durango (6,252 ha), and Nuevo León (4,173 ha) with remarkable nut production (77.8, 18.8, 18.4, 9, and 4.3 kt of harvested nut, respectively) (Herrera-Aguirre, pers. comm.). The importance of the pecan orchards as a carbon sink is even more relevant provided that the top 30 cm soil layer has SOC ranging from 1 to 105 t C ha^{-1} across the pecan-producing states (Figure 4). According to Lopez and Esteva (91), Chihuahua and Durango have their pecan orchards mostly planted in the east, precisely where soils are less C provided (4–30 t C ha $^{-1}$). Unlike the former states, Coahuila and Sonora have pecan production less concentrated and pecan orchards can be located at any point in the state (91). Knowing the distribution of the orchards allows for contextualizing the production for future trends. Considering the projection of climate change for Mexico, accounting with a plastic, adaptable woody species such as pecan is important provided that variables such as frost-free days and the number of hot nights are expected to increase within the next years, particularly in Chihuahua and Coahuila (92).

At the same time, the building back of SOM *via* the deposition of leaves, husks, and pruning residues is rather important under a

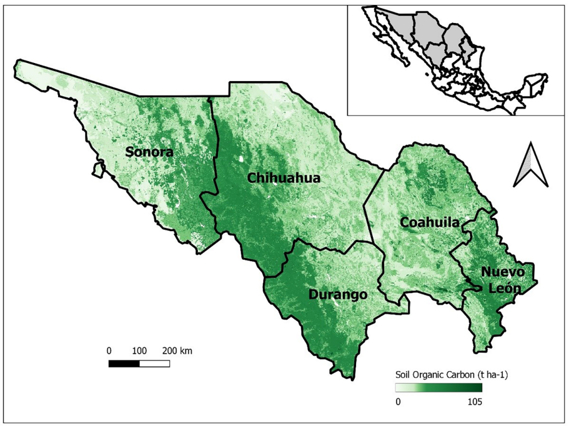

FIGURE 4
SOC for the Mexican states of Chihuahua, Coahuila, Durango, Nuevo León, and Sonora. Source: own elaboration in QGis v. 3.26.2 (2022) based on the Global Soil Carbon Map (84). The map in the upper right indicates the location of the states in Mexico.

scenario of low SOC and higher temperatures every year. In such a sense, from the perspective of C storage, there are many things to take into account in the Mexican context. Between 2005 and 2015, 46,938 ha were planted, resulting in plants aged from 7 to 17 years up to date (93). If we consider by a rather simple approach a homogeneous annual C sequestration rate of 9.11 t C ha^{-1} for mature orchards (18), an estimated pool of 204 kt C would be sequestered by 50% of the planted area during 2022 only, considering the current age strata of trees (93). Annually, this represents 68% of the C circulating the agroecosystem, out of which 29.5% remains in the trunk and branches and 41.3% returns to the soil *via* leaves and husks, with 13.4% stored as starch in the roots and 15.6% being harvested as nuts (16, 94).

Unlike the USA, Mexico exports a considerable amount of its domestic pecan production (65%), having an annual consumption *per capita* that is lower than that of the USA (16 g) and approximately half of the global mean (34 g) (13). From a nutritional point of view focused on SDG 2.2, the stimulation of domestic consumption of pecan represents an opportunity in this country since it may add diversity and balance to a daily intake mostly dominated by cereals and tubers (43.8% of the daily intake of energy) (95).

4.2 Pecans in South America: National trends, contribution to C stocks, and opportunities to match dietary needs

Unlike North America, South American countries have their pecan orchards mostly in the initial stage of implantation and production; thus, most of their trees have not yet attained the potential nut yield. Although most actions promoting the increase of planting area and nut production are being carried out in Brazil and Argentina, pecan is growing in importance in other South American countries like Uruguay and Peru.

4.2.1 Pecans in Brazil

In Brazil, the area planted with pecan is ca. 12,000 ha, with an estimated annual increase of 600 ha (Martins, pers. comm.), with most of the orchards being at a juvenile stage. The sector involves more than 1,850 growers distributed mainly in the states of Rio Grande do Sul (70%), Santa Catarina (22%), and Parana (8%) (96) (Figure 5). Brazilian pecan farmers have adopted both technology and new management techniques in order to cope with alternate bearing. The evolution of such improvements allowed the cycle 2020/21 to be the year with the highest pecan production in Brazil's history (5,500 t) since the average annual production is ca. 4,000 t (Martins, pres. comm.). Additionally, a recent edaphoclimatic survey performed by EMBRAPA detected 2.11 M ha in Parana, 3.65 M ha in Santa Catarina, and 11.34 M ha in Rio Grande do Sul suitable for pecan production. Thus, the pecan production is expected to grow even more during the coming years. From the point of view of management, the farmers adopt conventional rather than organic management, with the average farm occupying between 2 and 15 ha, and a basically familiar type of production (97).

The state of Rio Grande do Sul has its orchards located at the center-west (97), where soils have an average of 40 t C ha^{-1} (Figure 5), resembling Texas' soil conditions. Although orchards are mostly cultivated standalone, they complement crops such as tobacco (*Nicotiana tabacum*), rice (*Oryza sativa*), beans (*Phaseolus vulgaris*), soybeans (*Glycine max*), and cassava (*Manihot esculenta*) and are eventually integrated into either beef or dairy cattle production, resulting in silvopastoral systems (97). On one hand, given the agricultural landscape is dominated by the former-mentioned highly extracting and GHG-emitting crops, the pecan orchards constitute C sinks to offset these externalities. On the other hand, from the nutritional perspective, the domestic consumption of pecan nuts is also low (8 g per capita year^{-1}) when the total population is considered, but it 10-folds that amount if domestic consumption is weighed by the estimated percentage of usual nuts consumers (13). Given its nutritional benefits, the increase in pecan

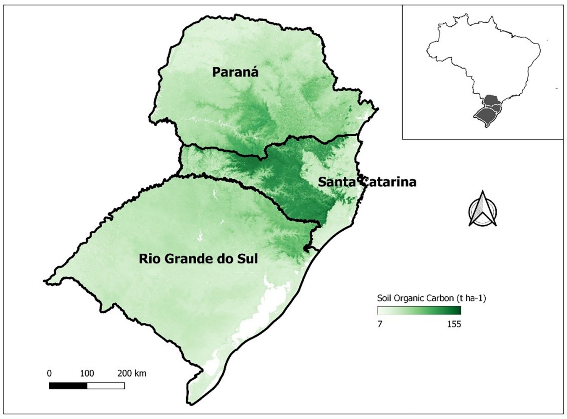

FIGURE 5
SOC for the Brazilian states of Rio Grande do Sul, Santa Catarina, and Paraná. Source: own elaboration in QGis v. 3.26.2 (2022) based on the Global Soil Carbon Map (84). The map in the upper right indicates the location of the states in Brazil.

consumption may help to attain SDG 2.2 and 2.4 in Brazil since 28.9% of the population is subjected to the prevalence of moderate to severe food insecurity and 22.1% of the population older than 18 suffer from being overweight with the risk of cardiovascular disease (95).

4.2.2 Pecans in Argentina

In Argentina, the pecan orchards are mostly concentrated in the provinces of Entre Ríos and Buenos Aires (64% of the national area), with nearly 8,000 ha planted to date (98). Within these provinces, the regions more climatically suitable to plant pecan are the Delta of the Paraná River, the Northeast of Buenos Aires, and the whole Entre Ríos province, although there is a small region in the Southeast of Buenos Aires where pecan may thrive (99) (Figure 6). These three regions have different ranges in SOC; while the Delta Region exhibits 85–142 t C ha^{-1}, Entre Ríos, Northeast of Buenos Aires, and Southeast of Buenos Aires have their orchards located at soils where SOC ranges 48–82, 41–89, and 82–106 t C ha^{-1}, respectively (Figure 6). Unlike Brazil, most orchards in Argentina are located in areas relatively well provided with SOC. Thus, in this case, pecan orchards may play a significant role in counterbalancing the CO_2 released by extensive agriculture.

The Argentinian pecan sector consists of 300–400 producers with most of them owning 15–50 ha, where pecan production complements their main agricultural business; however, there are a few specialized pecan companies that own up to 1,000 ha (100). The domestic market is still small, with a national *per capita* consumption estimated at 10 g yr^{-1}. Unlike the USA and Mexico, pecan nut consumption in Argentina is low compared to the global mean (34 g yr^{-1}); however, this year, Argentina launched a domestic and international pecan marketing campaign. Thus, these domestic consumption data are expected to change (101). In Argentina, the inclusion of nuts as pecan in the daily diet would help to diminish the prevalence of obesity in the 28.3% of the population older than 18, decreasing at the same time the risk of cardiovascular diseases (95).

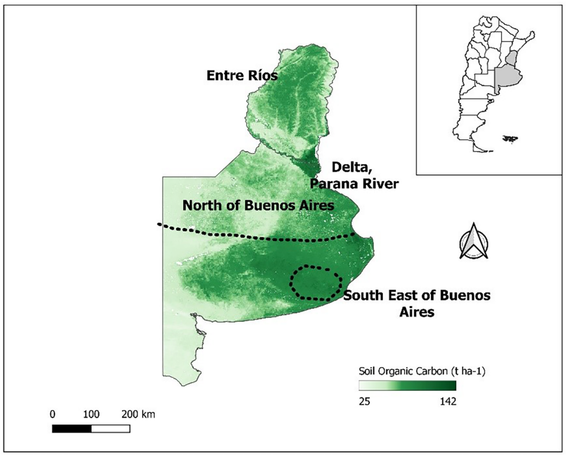

FIGURE 6
SOC for the provinces of Entre Ríos and Buenos Aires. Source: own elaboration in QGis v. 3.26.2 (2022) based on the Global Soil Carbon Map (84). Dotted lines indicate the most suitable area to plant pecan (99). The map in the upper right indicates the location of the provinces within Argentina.

4.2.3 Pecans in Uruguay and Peru

In Uruguay and Peru, pecan orchards are also in expansion. The surface occupied by pecan orchards in Uruguay is approximately 1,000 ha (Zoppolo, pers. comm.), with mostly 5 ha surface orchards distributed around the whole country. Planting is performed under conditions quite similar to those of the province of Entre Ríos in Argentina, with SOC ranging from 4 to 141 t ha^{-1} (Figure 7A). Furthermore, similarly to the previously mentioned countries of South America, most orchards planted in Uruguay can be considered still young, with the most emphasis on planting from 2009 onward, although the first plantations started around the ‘60s (102). Regardless of the latter consideration, the contribution of pecan to store C in Uruguay seems promising, even in a small area, to counterbalance methane emissions produced by beef cattle fed on rangelands. In a theoretical approach, if we consider a range of tree ages between 4 and 13 years (plantings between 2009 and 2018), with an annual surface increase of 75 ha and a starting point of 149 ha of mature trees (103), contribution to C storage during 2022 attains 3,675 t C ha^{-1}, what equals to have permanently removed 13,475 t CO_2 eq from the atmosphere during 2022. Regarding the nutritional perspective, the inclusion of pecan in the daily diet can help to correct diet imbalances observed in this country. For example, in 2016, 20.8% of Uruguayan women aged between 15 and 49 were found to suffer from anemia (95), an iron deficiency in the blood. Pecans are not only rich in iron but also in other micronutrients (Table 1); thus, the increase in pecan production

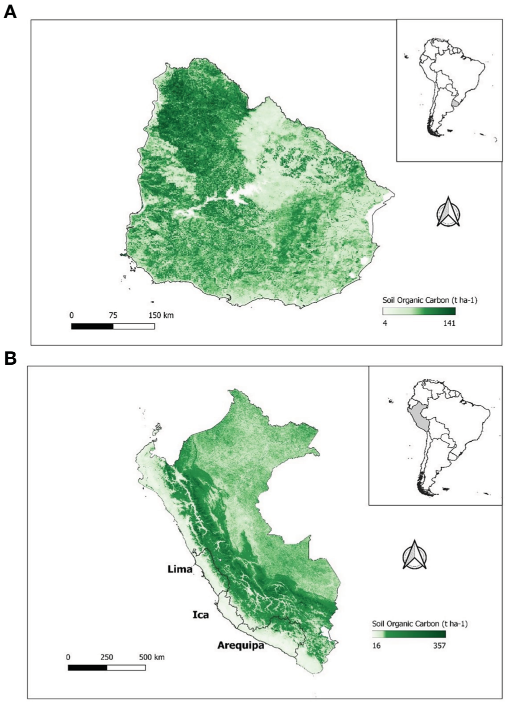

FIGURE 7
SOC in **(A)** Uruguay and **(B)** Peru. Source: own elaboration in QGis v. 3.26.2 (2022) based on the Global Soil Carbon Map (84).

for domestic consumption would help to improve such indicators leading to SDG 2.2.

In Peru, most of the pecan orchards are located in three departments: Ica (1,820 ha), Lima (400 ha), and Arequipa (130 ha) (Figure 7B), with 'Mahan' being the main cultivar planted (García, pers. comm.). The soil beneath these orchards has a shorter range than in the previously mentioned South American countries, with the department of Ica having the lowest SOC (18–50 t C ha^{-1}). Under that context, pecan orchards represent a unique opportunity to build SOC and resilience. Despite this, the information about pecan in Peru has not yet been published in scientific papers; rather, it results from empirical data and consultant agronomists' experience.

4.3 Contribution of pecan to carbon storage in the Americas

As repeatedly mentioned earlier, pecan trees represent a singular sink for atmospheric C; however, the literature seems to have overlooked the global dimension of this ecosystemic service for this edible fruit tree. Given this knowledge gap and through a rather simplistic method, we made the first approach by gathering the data of planted area during the period 2012–2022 for all the Americas' countries only excluding Peru due to the scarcity of temporal data. The planted area was multiplied by an estimated mean tree density of 70 trees ha^{-1}, and then, the mature pecan tree population by country was weighed by a biomass of 1.2 t tree^{-1} year^{-1} and a gain of 0.2 t year^{-1} tree^{-1} for mature trees (104). Immature trees were considered to have 50% of mature tree biomass and 50% of the yearly gain in biomass. Carbon stored in biomass was considered to be half the biomass, and CO_2 equivalents removed from the atmosphere were calculated by multiplying C stored in biomass by 44 and dividing it by 12.

The results shown in Table 3 reflect a statistical indicator that has been neglected in the bibliography so far: the existence of ca. 23 million pecan trees in the Americas (excluding Peru), storing 14 Mt C in their biomass or, what is the same, removing 51.3 Mt CO_2eq from the atmosphere. However, this is only part of the story since, if we consider a mean annual C sequestration rate of 9.11 t C ha^{-1} yr^{-1} (18) for mature trees only, including the vegetation surrounding pecan, and integrate the planted area from 2012 to 2022, the cumulative stored C in the system (pecan biomass + soil) during that period results in 21.92 Mt C, having removed 80.36 Mt CO_2eq, with mature orchards occupying 72.3%–77.3% of the planted area in the Americas for the considered period. This denotes not only the environmental potential of pecan orchards as C sinks alone but also a hypothetical increase in C sequestration when integrated into other activities, for example, silvopastoral systems or alley crops. Although we found some studies on pecan pioneering with calculations of this sort (16, 94), future studies should provide friendly tools for pecan farmers to be able to calculate environmental gains in their orchards.

5 Pecan as a platform to integrated sustainable systems

Agroforestry has been defined as a combination of woody plants with either crop (silvoarable systems) or cattle (silvopastoral

TABLE 3 Tree population and C stored in pecan trees' biomass during the period 2012-2022 for USA, Mexico, Brazil Argentina and Uruguay.

	USA*		Mexico**		Brazil***		Argentina***		Uruguay****		C Stored Total	
Year	Trees (mill.)	Stored C (Mt C)	Trees (mill.)	Stored C (Mt C)	Trees (mill.)	Stored C (Mt C)	Trees (mill.)	Stored C (Mt C)	Trees (mill.)	Stored C (Mt C)	Mt C	Mt Coeq
2012	13.21	7.27	6.30	3.14	0.088	0.03	0.07	0.02	0.03	0.01	10.5	38.4
2013	12.78	8.21	6.68	3.78	0.140	0.06	0.09	0.03	0.04	0.02	12.1	44.3
2014	12.34	7.93	7.06	3.96	0.193	0.08	0.11	0.04	0.04	0.02	12.0	44.1
2015	11.91	7.66	7.44	4.17	0.245	0.10	0.12	0.05	0.05	0.02	12.0	44.0
2016	11.13	7.14	7.83	4.52	0.298	0.12	0.14	0.06	0.05	0.02	11.9	43.5
2017	11.21	7.20	8.21	4.74	0.350	0.15	0.18	0.07	0.06	0.03	12.2	44.7
2018	11.29	7.25	8.59	4.96	0.452	0.20	0.21	0.09	0.06	0.03	12.5	45.9
2019	11.37	7.30	8.97	5.18	0.553	0.26	0.25	0.10	0.07	0.03	12.9	47.2
2020	11.46	7.35	9.35	5.40	0.655	0.32	0.35	0.15	0.07	0.03	13.3	48.6
2021	11.54	7.41	9.73	5.62	0.756	0.37	0.46	0.19	0.08	0.04	13.6	50.0
2022	11.62	7.46	10.11	5.84	0.840	0.42	0.56	0.25	0.08	0.04	14.0	51.3

*Calculations made considering 70 trees ha^{-1} as mean density and the information of planted area in Wells (86), Herrera-Aguirre and Lopez Díaz (93), and data of NASS USDA (82).
** Planted area taken from Herrera-Aguirre and Lopez Díaz (93) and Herrera-Aguirre (pers. comm.).
*** Data from Martins et al. (97) and Martins (pers. comm).
**** Planted area based on Sec. Agroindustria (105), Frusso (98) and Frusso (pers. comm) and Lavista Llanos (106).
***** Planted area according to Tanaka Vidal and García Pintos (103).
Carbon per plant calculated according to biomass per mature plant estimated by Kraimer et al. (104) and Wells (107).

systems), aiming to capture the economic and ecological benefits of such interaction (108). In such a sense, pecan orchards fit perfectly with that definition since they may be integrated not only to winter crops such as wheat and barley due to its deciduous nature but also to beef or dairy cattle given the possibility of seeding high-quality pastures between plant rows. Therefore, pecan orchards can provide a platform to be combined with either agri-food system, leading to integrated sustainable systems (ISS). When the query "agroforestry" is introduced in the Scopus science browser for the period 2011–2020, 5,965 articles were found, with half of the articles written in nine countries: USA, Brazil, India, Germany, Indonesia, China, France, the United Kingdom, and Spain (109). If the search is refined to tree nuts, the total of studies produced during that period is 27, out of which 4 were related to pecans.

In such a sense, there are recent standalone studies that evaluated the economic and environmental dimensions of pecan as integrated into other systems. On one hand, Moore et al. (110) determined the economic value of sustaining a silvopastoral system compound by native pecan and stocker cattle grazing for 90 days and found that mutually beneficial. On the other hand, other studies demonstrated that integrating cover crops into pecans enhanced the prevalence of mycorrhizal fungi, with ectomycorrhizal fungi located in the tree rows and arbuscular mycorrhizal fungi located in the alleys, both boosting SOC (111). The novel study supported the evidence found by Kremmer and Kussman (112) on the effects of cover crops on soil quality under a pecan orchard. Additionally, Cabrera-Rodriguez et al. (113) found that, under an organically managed pecan orchard, the capture of recalcitrant carbon was supported by a greater diversity of bacterial communities, while, in a conventionally managed orchard, SOC mineralization and enzymatic activity to metabolize labile C were stronger. In terms of circularity, Noperi-Mosequeda et al. (63) found that combined mineral and organic fertilizers support the production and preserve nut quality ranges, increasing the phenolic compounds and antioxidant capacity.

Regarding alley cropping in pecan orchards, there are studies evaluating competition for water (114) and light (115) between cotton (*Gossypium hirsutum*) and 50-year-old pecans in Florida with cotton alley-cropped at 23,600 seeds ha^{-1} within a distance of 18.3 m of spacing between tree rows. The former studies concluded that this alley crop is a valid alternative to producing lint and nuts for the southeastern USA. Additionally, Yadav et al. (116) evaluated a densely planted pecan orchard (277 pl ha^{-1}) in the Himalayas, alley-cropped with lentil (*Lens esculentum*), finger millet (*Eluesine coracana*), wheat (*Triticum aestivum*), and soybean (*G. max*) for 7 years, concluding that although the sole cropping situation provides better yields, there are environmental gains in diversifying through alley cropping (more C) and, above all, increased returns when the global yield (grains + nuts) is considered.

As a final remark, the pecan orchard as a platform for ISS can provide many services other than economic such as nutritional diversity, carbon sequestration, and comfort for animals when integrated into animal production systems. Furthermore, this integration may help to reduce crops and cattle C footprint since, as shown in Poore and Nemececk (117), the C footprint for nuts is very small [1.61 kg CO_2 eq kg $nuts^{-1}$ for pecans, 118)], while beef meat C footprint rounds 60 kg CO_2 eq kg meat.

6 Pecan orchards as sink for carbon sequestration in aboveground and belowground biomass

6.1 Carbon sequestration in above ground biomass

The global apprehension is that carbon management should be in forests to mitigate the increased concentration of greenhouse gases in the atmosphere. However, the worldwide forest cover is diminishing fast in view of great biotic stress, industrialization, urbanization, land use changes for developmental activities, and the conversion of forests to agricultural land. The importance of terrestrial vegetation as significant sinks of atmospheric carbon dioxide and its other derivatives is highlighted under the Kyoto Protocol (119).

Pecan trees have recently drawn attention as climate-smart production systems for temperate regions as they can provide high net carbon (C) gains per area and generally occupy a relatively small fraction of the agricultural landscape (44). Pecan trees form an important component in the different production forest systems, which provide extensive ecosystem services. In this context, biomass and carbon inventory in these production systems are essential (119).

Pecans are grown in many climates under different environmental conditions, and this diversity can generate variations in the carbon sequestration in aboveground biomass between regions. In the wetter areas of the USA, pecans can grow much larger and at rates different than in the arid Southwest, simply as a result of soil moisture. Usually, the age structure of the pecan population in humid regions is older than in the West. Although this may not be good for the constant production of pecan, the longer a tree lives, the more carbon is stored in aboveground biomass (107).

Globally, the estimated range between 40 and 150 t C ha^{-1} is the average quantity of carbon stored in the aboveground components of agroforestry systems (19). One of the most important benefits of pecan trees is their high photosynthetic rate due to their long phenology, which increases its potential annual atmospheric CO_2 capture (18). The pecan can store significant amounts of carbon in aboveground biomass for a long time. Based on the calculations of Kraimer et al. (104), a mature pecan (approximately 15 years old) has a biomass of 1.2 t per tree and accumulates approximately 0.2 t of biomass per year, depending on climatic and edaphic conditions and nutritional and cultural management (107).

Carrying out studies related to carbon sequestration in aerial biomass in pecan forests, associated with different production systems in India, the tree density of an 11-year-old *C. illinoinensis* orchard was 238 trees ha^{-1}, and the total tree basal area was 6.11 m^2 ha^{-1}. The pecan orchard had a mean diameter at chest height (dbh) of 18.04 cm and a wood volume of 0.266 m^3. The maximum values of biomass (56.5 t ha^{-1}) and carbon (25.3 t ha^{-1}) were determined (119). With annual herbaceous productions cultivated between pecan lines, these mixed productions raise the possibility of maximizing global production per surface unit, evaluating positive interactions between pecan and herbaceous crops, and controlling weed development.

Tests carried out with organic amendments recorded a significant increase in both height and diameter (Figure 8).

Timber production in pecan silvopastures is often neglected despite pecan's wood use for cabinetmaking, paneling, furniture, and flooring (121). Most pecan timber comes from tree thinning aimed at reducing overcrowding to sustain nut production. A fundamental step towards the improvement in the management of the timber resource in pecan silvopastures is the determination of standing stocks and annual increments, thus enabling the derivation of potential extraction rates (122).

In summary, pecan orchards represent an important reservoir of C in the aerial biomass, representing a stable compartment of the CO_2 fixed from the atmosphere, given the longevity of the tree and its potential timber use. In addition to the commercialization of nuts, the implementation of walnut forests is considered of great environmental and commercial value.

6.2 Belowground carbon sequestration and soil quality improvement

Pecan trees require approximately 12–15 years of growth after establishment to deliver economic yield with nuts; thus, the use of an agroforestry system where the alley between tree rows can be used with perennial crops can be used to sustain livelihood security and maintain soil cover and quality (112). In addition to the diversification of products that the agroforestry system with pecan delivers (food, fodder, fruit, pruned material such as firewood, nuts, etc.), it provides carbon sequestration, capturing CO_2 from the atmosphere and storing it in the soil as organic matter–stabilized forms, while increasing productivity (116).

Agroforestry system with pecan has the potential to increase soil fertility and microbial biomass carbon due to the constant input of the deciduous leaves and root turnover to the soil in a long term (47 years). The presence of older trees also leads to a shading effect, with a reduction in soil temperature and an increase in soil moisture, fine root biomass, and soil carbon content when compared to young trees (17). Another agroforestry system with pecan in the Ozark Highlands region of northwest Arkansas, United States, that received poultry litter as organic fertilizer for 17 years increased superficial (0–15 cm) nutrient concentrations and reduced bulk density when compared to inorganic fertilization (123). That management practice was reflected in higher soil organic matter concentrations and soil carbon stock, which was also influenced by the differential decomposition of pecan leaf litter (123). In that same agroforestry system study, pecan soil that received poultry litter application got higher soil quality index (SQI) than agroforestry with red oak (124). The SQI index used soil organic carbon, pH, P, K, and bulk density as part of the methodology Soil Management Assessment Framework (SMAF), which is a quantitative soil quality evaluation tool that is used to check soil responses to management systems (125).

The pecan orchards with organic management have increased concentrations of nitrogen, microbial biomass carbon, and soil organic carbon when compared to conventional practices (113). Furthermore, the soil organic matter in the organic pecan management is more stabilized than more recalcitrant forms, reducing the CO_2 released to the atmosphere, which promotes more efficiency in carbon sequestration when compared to conventional management (113). In an agroforestry system with 19-year-old pecan trees (*C. illinoinensis*) and bluegrass *(Poa trivialis*), the total soil organic carbon and total nitrogen were higher in the tree rows than in the middle of the alley, but it found no difference in the particulate organic matter and microbial biomass carbon between those sites (126). Litter quality also influences soil carbon dynamic, as found in a 21-year-old pecan and bluegrass (*P. trivialis*) intercrop study in which the bluegrass litter mineralized significantly higher amounts of C and decomposed 2.3 times faster than pecan litter, which has higher C:N and lignin compounds (127).

Additionally, aged, mature pecan orchards present better soil aggregate stability, mostly because of the higher levels of soil organic matter and microbial activity, which result in better soil quality when compared to row crop fields (61). Pecan roots are capable of increasing nutrient cycling and cation exchange capacity (CEC) as

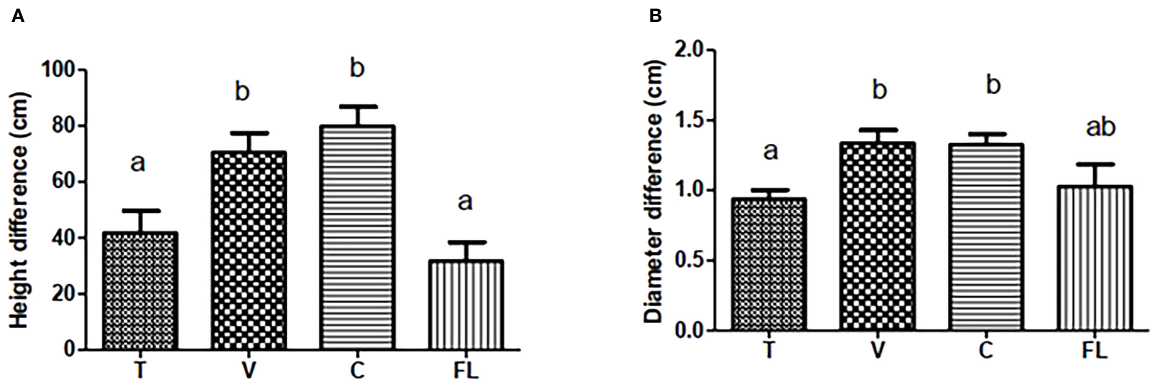

FIGURE 8
Mean values of control treatment (T), vermicompost (V), compost (C), and liquid fertilizer (FL). Significant differences are shown in **(A, B)**. References: **(A)** differences in plant height and **(B)** differences in plant diameter between two consecutive years (adapted from (120)).

they can remove nitrogen from the deeper soil profiles and bring it to the upper layers and can also reduce nitrate leaching below the root zone (61). The use of a perennial cover cropping with Kura clover (a nitrogen-fixing legume) between pecan tree rows in an agroforestry system promoted a restoration of soil physical properties by rhizodeposition, which encouraged soil-stable aggregation, reducing erodibility and enhancing soil organic matter and providing economic benefits for pecan while achieving maturation (112). Deficiency in mineral nitrogen in pecans may lead to nutrient imbalance and toxicity; thus, that nutrient is very important for the growth and development of that species, which is more inclined to use NH_4^+–N than NO_3^--N, with a ratio of 75:25 considered the most favorable for pecan seedlings (128).

As observed in this part of the review, there are some studies that assessed soil and nitrogen soil content, but few studies evaluate soil carbon stock in pecan orchards and their potential to increase it when compared to a monoculture or native vegetation. That marks a research gap in the study of the environmental aspect of pecan for climate resilience production.

7 Conclusions

Throughout this analysis, it was repeatedly observed that pecan is a reliable sink for storing atmospheric C and producing quality food with high nutritional density. The Americas has a diversity of soils where pecan orchards are planted, with SOC ranging from less favorable (Perú and México) to relatively high (Brazil, Uruguay, and Argentina). Despite these ecological differences, a population of ca. 23 M trees prevails, with the younger tree populations and the highest C-storing potential in South America. This pecan tree population has removed 51.3 Mt CO_2eq, immobilizing the OC in their aboveground biomass, but, if the C sequestration for the whole system is considered, the value reaches nearly 80 Mt CO_2eq in three-quarters of the planted area. Therefore, the potential of pecan orchards to store C is a research topic with an enormous prospect and is useful for designing national plans for GHG mitigation measurements.

From a nutritional perspective, there are different dietary needs to cover according to the country, although the common analysis is a low proportion of nuts in the diet, which is expected to improve, given each country's efforts to promote domestic consumption. All the countries mentioned in this study have low pecan consumption going from 8 to 293 g per capita yr^{-1}, which, in light of the Global Burden of Disease (4), represents 0.08%–3.2% of the recommended yearly dietary basis for nuts overall. Increasing the inclusion of pecans in the diet is the most important method to cope with the food nutrient dilution produced by the effect of atmospheric CO_2 fertilization.

The third remark goes about pecan orchards' function as a platform to integrate sustainable systems. Even though the studies found are still few, the global benefit of having pecan and alley crops has been proven in regions other than the Americas with interesting economic outputs, leading to energizing the life of rural communities. In America, we found several studies about the integration between pecan orchards and cotton, although all of them performed at the level of competition by resources (water and light) between species. We also found one study about the profitability of combining pecan and stocker cattle.

Finally, pecan orchards and pecan agroforestry may lead to sustainable agri-food systems, with global gains in SOC and nutritional richness and diversity. Therefore, more in-depth studies related to C cycling in the orchard, links between the nutritional composition of pecan nuts, and tools to calculate C budget are needed to not only fully understand the functioning of the systems at the productive level but also allow stakeholders to design and plan sustainable pecan orchards in rural areas.

Author contributions

GC took the lead in writing and shaping the manuscript. EF revised critically the manuscript and provided the contact of the other authors. EH-A revised critically the manuscript and significantly contributed to Section 4. RZ revised critically the manuscript and significantly contributed to Section 3. FL significantly contributed to Sections 2.1 and 6.2. MB significantly contributed to Section 2.2. CMa significantly contributed to Section 4.2. CMe significantly contributed to Section 6.1. All authors contributed to the article and approved the submitted version.

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Conflict of interest

CMa was employed by the company Embrapa. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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