

**SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY****Carbon dioxide net assimilation exchange in a young pecan nut orchard during the growth cycle**A. Zermeño-Gonzalez^{1*}, E.A. Jimenez-Alcala¹, J.A. Gil-Marin¹, H. Ramírez-Rodríguez², M. Cadena-Zapata³, I.A. Melendres-Alvarez¹¹ Irrigation and Drainage Department, Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México² Department of Horticulture, Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México³ Agricultural Machinery Department, Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México**ARTICLE INFO****Article History:**

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ABSTRACT**BACKGROUND AND OBJECTIVES:** Pecan nut trees (*Carya illinoensis* K), due to their condition as woody and long-living species, in addition to the contribution of nuts for consumption, may also have an essential role in assimilating carbon dioxide and sequestering atmospheric carbon. This study aimed to determine the carbon dioxide net ecosystem exchange of an orchard of young pecan nut trees in northern Mexico, and its relationship with the growth months of the trees.**METHODS:** The study was carried out from March to November 2017 in a six-year-old pecan nut tree orchard containing trees of the Western Schley and Wichita varieties. The orchard is drip-irrigated with buried tape. The carbon dioxide net ecosystem exchange between the canopy of the orchard trees and the atmosphere was determined with eddy covariance measurements using a three-dimensional sonic anemometer and an open-path infrared carbon dioxide analyzer.**FINDINGS:** The highest daytime carbon dioxide net ecosystem exchange rate corresponded with the peak absorption rate of photosynthetically active radiation absorbed by the trees' canopy. It was observed between 11:00 and 14:00 hours throughout the growth months of the trees. The highest carbon dioxide net ecosystem exchange rate was observed in June, at 7 micro mol square meter per second. The relationship between the carbon dioxide net ecosystem exchange and the photosynthetically active radiation absorbed by the trees' canopy through the growth months was described using a rectangular hyperbolic function. From March to September, the carbon sequestration of the young pecan nuts was 0.962 tons of carbon per hectare.**CONCLUSION:** The highest carbon dioxide diurnal assimilation rate was observed in May, at 5 717.95 millimoles per square meter. Despite the young age of the pecan trees, the orchard has a retention capacity of 0.962 tons of carbon per hectare for the months evaluated. The young pecan orchard significantly contributes to the assimilation and retention of atmospheric carbon that will increase with the growth of the trees, due to greater leaf and biomass development.DOI: [10.22034/GJESM.2023.09.SI.06](https://doi.org/10.22034/GJESM.2023.09.SI.06)This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

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INTRODUCTION

Carbon dioxide (CO₂) is a greenhouse gas, generated by burning fossil fuels, that induces global warming and climate change (Gizer et al., 2022; Rehman et al., 2022; Prasara-A and Bridhikitti, 2022). Plant ecosystems also absorb this gas (photosynthesis process) for their growth and development (Pimienta, 2007; Garsetiasih et al., 2022; Hidayah et al., 2022). The study of the dynamics of CO₂ flux between plant ecosystems and the atmosphere is important due to its relationship with global warming. The contribution of vegetation to the global carbon cycle is fundamental due to atmospheric carbon sequestration in plants' biomass (Eftekhari, 2022; Sahoo et al., 2022; Dhayalan and Karuppasamy, 2021). Previous studies on the CO₂ assimilation rate and atmospheric carbon sequestration have been carried out in various natural plant ecosystems. For example, the study of Bernal et al. (2018) reported the CO₂ assimilation rate, in tons of CO₂ per hectare per year (t/CO₂/ha/y), of a conifer forest in a boreal climate, and of Eucalyptus (*Eucalyptus globulus*) in a tropical humid zone. The rate of carbon sequestration (t/C/ha/y) of inland wetlands, peatlands, and coastal wetlands was reported by Li et al. (2023). In another study, in a forest of the species *Gmelina arborea*, *Eucalyptus tereticornis*, *Cassia siamea*, and *Leucaena leucocephala*, carbon sequestration potential was evaluated (Kaith et al., 2023). However, there is not much information on the participation of agricultural systems in this context (Rojas-García et al., 2015; Sharman et al., 2021). Due to their condition as woody and long-living plant species, pecan nut (*Carya illinoensis* K.) trees, in addition to their use for walnut production, may play an essential role in CO₂ assimilation and atmospheric carbon sequestration. The average biomass accumulation in a mature pecan orchard can reach up to 22 tons per hectare (t/ha) (Wang et al., 2007; Dold et al., 2019). In Mexico, pecan walnut cultivation began in the state of Chihuahua 400 years (y) ago, and the establishment of orchards for commercial purposes dates back to 1946; therein, currently, there are trees up to 71 y old (Ojeda-Barrios et al., 2009; Concilco-Alberto et al., 2022). Most of the studies carried out recently on pecan nut trees have been oriented mainly to the agronomic management of the crop, such as pruning, phytosanitary control, fertilization, trees' water requirements, and irrigation scheduling

(Samani et al., 2011; Zermeño-González et al., 2014). For example, Andales et al. (2006) studied effective pruning management using a growth simulation model. Bock et al. (2012) evaluated the effect of a fungicide on controlling walnut scabs. Ojeda-Barrios et al. (2014) performed foliar fertilization with Zinc to improve yield in an eight-year-old pecan nut orchard. Samani et al. (2011) and Zermeño-Gonzalez et al. (2014) used the eddy covariance method to measure water vapor and CO₂ fluxes between the canopy of a pecan nut orchard and the atmosphere. Mexico is the leading exporter of shelled pecan nuts to the United States (Retes et al., 2021), so its planted surface has increased significantly recently. In 2021, a total plant cover of 146,239.11 hectares (ha) of pecan nut orchards was reported, wherein the states of Chihuahua, Coahuila, Sonora, Durango, and Nuevo León accounted for 60.9, 14.9, 13.34, 5.2 and 2.9 percent (%) of total production, respectively (SIAP, 2021). The global increase in pecan orchards' establishment may contribute to CO₂ assimilation and atmospheric carbon storage. Under the hypothesis that young pecan nut trees may contribute to atmospheric carbon sequestration, the objective of this study was to determine the CO₂ net ecosystem exchange of an orchard of young pecan nut trees throughout the growth months in northern Mexico during the growing cycle of the year 2017.

MATERIALS AND METHODS

Study site

The study was carried out from March to November 2017 in a six-year-old pecan walnut (*Carya illinoensis* K.) orchard located in the General Cepeda Municipality, Coahuila State, Mexico (25° 28' 22.46" North (N), 101° 26' 40.06" West (W), at 1304 meters (m) above sea level (masl). According to the Modified Köppen Classification for Mexico, General Cepeda has a climate of the type BSOh'(h)x'(w)(e') (Copers, 2020), which is an arid, semi-warm climate. The average yearly temperature and average rainfall are 18.3 degrees Celsius (°C) and 265 mm, respectively. The pecan nut trees are planted in a rectangular planting framework, aligned in the north-south direction, with a spacing of 8 m between trees and 12 m between rows, covering an area of 11.6 ha. The varieties planted are Western Schley and Wichita. The orchard is drip-irrigated (with tapes buried 20 cm deep), the hoses are 1 m apart from each side of the

trunk of the trees, and there are 16 emitters per tree (8 on each side) spaced 60 cm apart with a flow rate of 1.68 liters per hour (LPH). Two 12-hour irrigations are applied every six days.

Measurements and sensors

The CO₂ flux between the orchard canopy and the atmosphere was obtained with eddy covariance measurements using Eq. 1 (Zermeño-Gonzalez *et al.*, 2021):

$$FCO_2 = w * P_{CO_2} \quad (1)$$

where w is the vertical wind speed and p_{CO_2} is the density of CO₂. Variables with a prime symbol are the deviations from the mean, and the horizontal bar corresponds to the covariance between the variables for a specific time segment (30 min). The vertical wind speed (w) was determined with a three-dimensional sonic anemometer (CSI-CSAT3, Campbell Scientific, Inc., Logan, Utah, USA). The density of CO₂ in the air was measured with an open-path infrared analyzer (Open Path CO₂/H₂O analyzer, LI-7500. LICOR, Lincoln, Nebraska, USA). Both sensors were placed at the center of the southern end of the orchard, 2 m above the trees' canopy, and connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, Utah, USA) to record the data. The three-dimensional sonic anemometer was oriented north so that the wind had at least 300 m of contact with the surface in the north–south direction, and 125 m in the east–west direction, before contact with the sensors. The operating frequency of the sensors was 10 Hz, and the covariances were generated at intervals of 30 min. The climatic conditions vary daily; however, the eddy covariance measurements also register the daily changes in weather data. The CO₂ net ecosystem exchange (NEE) (μmol/CO₂/m/s) between the orchard canopy and the atmosphere was obtained using Eq. 2 (Martens *et al.*, 2004):

$$NEE = FCO_2 + \frac{\Delta \rho CO_2}{\Delta t} \Delta z \quad (2)$$

where FCO_2 is the flux of CO₂ measured with the eddy covariance method (Equation 1) (negative sign towards the surface), and $\Delta \rho CO_2$ is the change of CO₂ density in a particular time segment Δt (30 min). Δz is the height above the ground surface at which flow

measurements are made (5 m). The daily balance of the CO₂ NEE through the growth stages of the trees was obtained using the difference between the daytime (assimilation) and night-time (release) integrated values. The rate of photosynthetically active radiation (PAR) absorbed by the trees' canopy was obtained by placing two quantum sensors (model SQ-512, Apogee Inst., Logan, Utah, USA) 2 m above the tree canopy, one oriented toward the midpoint of a tree canopy (reflected PAR) and the other toward the zenith (incident PAR). The PAR absorbed by the trees' canopy was the difference between the incident and reflected PAR. Measurements were made at a frequency of 1 Hz (with the sensors connected to another CR1000 datalogger), and 30-min averages were obtained. The eddy covariance system measures the exchange of CO₂ fluxes from the atmosphere to the soil and the pecan trees. The CO₂ from and towards the ground depends on the soil properties (organic matter and water content, microorganisms, among others). Using the eddy covariance measurements, the CO₂ flux from the soil is considered. Fig. 1 shows an image of the orchard and the sensors used to take the corresponding measurements.

Relationship between the CO₂ NEE and the PAR absorbed by the trees' canopy

To assess the relationship between the CO₂ NEE and the PAR absorbed by the trees' canopy, we used a rectangular hyperbolic function, as shown in Eq. 3 (Stoy *et al.*, 2006; Moffat *et al.*, 2007):

$$NEE = \frac{b1 * PAR}{b2 + PAR} + b3 \quad (3)$$

where $b1$ represents the highest photosynthetic capacity of the ecosystem (μmol/m²/s), $b2$ corresponds to the PAR value for the mean value of the photosynthesis rate (μmol/m²/s), and $b3$ symbolizes the daytime respiration rate of the ecosystem (μmol/m²/s). These parameters were obtained using nonlinear regression procedures (i.e., evaluations of functions using the Jacobian method).

Quantum yield and quantum efficiency of the orchard trees

The quantum yield (μmol CO₂/mmol photons) of



Fig. 1: Pecan nuts of 7-year-old trees and the sensors for eddy covariance measurements of the CO₂ net ecosystem exchange (NEE) and photosynthetically active radiation (PAR) above the trees' canopy

the orchard trees throughout the months of growth was obtained by dividing the moles of CO₂ assimilated during the daytime (NEE) by the mmol of photons absorbed at the same time (PAR). The quantum efficiency (%) was found using the relationship between the energy required (MJ) for the assimilation of the CO₂ moles and the energy content (MJ) in the PAR absorbed by the trees' canopy.

Statistical analysis

The differences in the trees' quantum yield and quantum efficiency during the growth months were evaluated using a completely randomized design. Each month was considered one treatment (using a total of seven months), and the repetitions were the number of days with information from each month. A Tukey's test ($\alpha \leq 0.05$) was used to compare the treatment means.

RESULTS AND DISCUSSION

CO₂ NEE and absorbed PAR

As the leaf area grows, the CO₂ assimilation rate increases, and the opposite occurs when the leaf area is reduced. At the beginning of the vegetative stage (March), the leaves of the trees were beginning their

development, and the CO₂ net ecosystem exchange rate (NEE) (30 min averages) of the orchard trees was minimal compared to that observed in the following months (Fig. 2). During this stage, the CO₂ net ecosystem assimilation rate (the negative sign of NEE in Fig. 1) was, on average, less than $-1.25 \mu\text{mol}/\text{m}^2/\text{s}$; of approximately the same magnitude was the highest CO₂ net ecosystem release rate (the positive sign of NEE in Fig. 2) (night-time respiration), and this represents an approximate balance between the rate of assimilation and the release of CO₂ of the ecosystem. The highest daytime CO₂ NEE assimilation rate corresponded to the peak rate of photosynthetically active radiation (PAR) absorbed by the trees' canopy. This was observed between 11:00 and 14:00 throughout the growth months of the trees (Fig. 2). Due to the limited development of the trees' canopy during March, the absorbed PAR rate was lower ($1\,700 \mu\text{mol}/\text{m}^2/\text{s}$) than that observed in the following months (Fig. 2). In June, when the trees already had full leaf development and the uppermost photosynthetic activity, the maximum daylight hours' CO₂ assimilation rate was up to $-7 \mu\text{mol}/\text{m}^2/\text{s}$, while the (night-time) release rate was only $2 \mu\text{mol}/\text{m}^2/\text{s}$ (Fig. 2). The rate of assimilation being greater than the rate of release is due to the formation

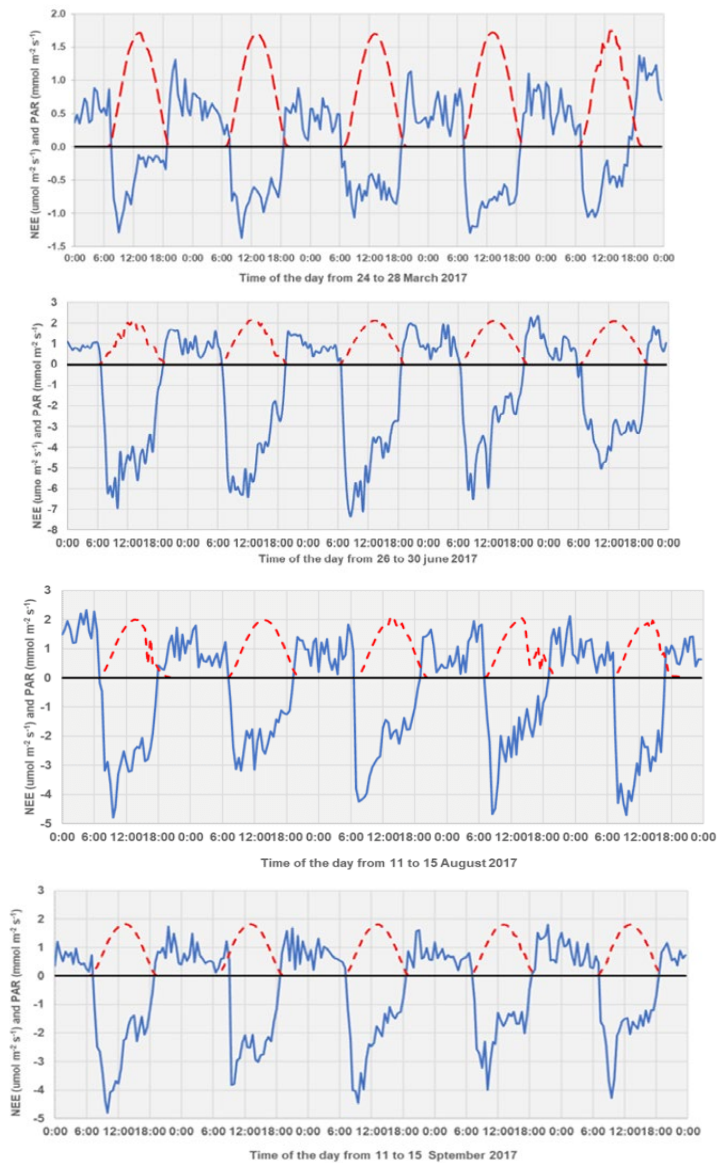


Fig. 2: CO₂ net ecosystem exchange rate (30 min average) (NEE) (the solid blue line), and photosynthetically active radiation absorbed by the tree canopy (PAR) (dashed red line), from an orchard of 7-year-old pecan trees at different times in their growth cycle.

of carbon compounds that can be used for wood growth and fruit development. In this regard, Wang *et al.* (2007) and Negi *et al.* (2003) mention that of the total assimilated CO₂, 46.4 % is allocated to the growth and formation of wood and fruits. The rate of PAR absorbed by the trees' canopy was up to 2 100 μmol/m²/s. In August, the highest CO₂ daytime assimilation rate decreased to slightly lower values (-5 μmol/m²/s),

while the greatest CO₂ night-time release rate was up to 2 μmol/m²/s, with the highest rate of PAR (up to 2000 μmol/m²/s) being absorbed (Fig. 2). During September, the rate of the highest CO₂ assimilation was also -5 μmol/m²/s, but the rate of the highest CO₂ release was less than 2 μmol/m²/s, and the rate of maximum PAR absorbed was slightly less than 2 000 μmol/m²/s (Fig. 2). Similar patterns have been observed in other crops.

For example, in a Kiwi (*Actinidia deliciosa*) orchard, the CO₂ assimilation peaked during May and June (up to -14 μmol/m²/s) and decreased to -12 and -10 μmol/m²/s in July and August, respectively (Rossi et al., 2007). In a mature avocado (*Persea americana* Miller) orchard, the peak net assimilation rate was observed in April (-18.3 μmol/m²/s), and decreased to a constant value (-10 μmol/m²/s) in October (Nafees et al., 2019). The CO₂ net ecosystem exchange values observed in this study are small, as the orchard was made up of young trees (of 7 years old) that had an average crown diameter of 4.78 m, which is equivalent to an area of only 15.75 m². This crown surface only covered 16.4 % of the total soil surface in a planting framework that had 12 m between lines and 8 m between trees. Most previous studies have been carried out in orchards of older pecan trees with a greater leaf area and biomass, and higher CO₂ assimilation rates. The CO₂ assimilation rate depends more on the trees' leaf area than the cultivar. In a pecan orchard of 35 y old trees wherein the canopy covers the whole soil surface, the CO₂ assimilation rate can be up to -17 μmol/m²/s (Zermeño-Gonzalez et al., 2014). The CO₂ NEE of three pecan nut genotypes (A1, A3, and A9) under pot growth conditions was -26.3, -25.6, and -27.5 μmol/m²/s, respectively (Momayyezi et al., 2022). In 25-year-old pecan nut trees of the cultivars Pawnee and Stuart, the CO₂ NEE rate was -11 and -9 μmol/m²/s, respectively, for a PAR assimilation rate of approximately 700 μmol/m²/s. (Lombardini et al., 2009). For the Franquette cultivar (12-year-old trees), the CO₂ NEE was up to -16.9 μmol/m²/s (Christopoulos et al., 2021). Although weather conditions change during the hours of the day, from day to day, and from month to month, the results of this study showed that at the time of the highest incidence of solar radiation, the photosynthetically active radiation absorbed by the trees' canopy and the CO₂ net ecosystem exchange also have the highest values, and this applies from year to year.

Relationship between CO₂ NEE and PAR

The energy required for CO₂ assimilation is provided by solar radiation within the wavelength of 400 to 700 nanometers (nm). The relationship between CO₂ net ecosystem exchange (NEE) and the photosynthetically active radiation (PAR) absorbed by the trees' canopy (average of 30 min) through the growth months was described with a rectangular hyperbolic function (Fig. 3). This function depicts an increase in NEE (a bigger

negative value) as the absorbed PAR increases. The NEE capacity of the canopy trees depends on the stage of growth. The trees had little foliar development in March and a low CO₂ absorption rate. For a PAR absorption rate of 1000 μmol/m²/s, the NEE rate was -1.0 μmol/m²/s. In May, the NEE increased to - 4.5 μmol/m²/s for the same PAR absorption rate. In July, the same rate was 4.0 μmol/m²/s, and in September, it decreased to -2.9 μmol/m²/s (Fig. 2). Similar relationships have been observed in other plant ecosystems. In a plum (*Spondias purpurea* L.) orchard, the peak photosynthesis rate was up to -10.7 μmol/m²/s on the days of the highest incidence of PAR (Ramirez and Pimienta, 2003). For four-year-old rubber plants (*Hevea brasiliensis* Müll. Arg.), the NEE reached a saturation of -25 μmol/m²/s at an incident PAR of 700 μmol/m²/s (Chayawat et al., 2019). The coefficients b₁ and b₃ of the rectangular hyperbolic equation are indicators of the highest photosynthetic capacity and the daytime respiration rate of the orchard, respectively (μmol/m²/s). Table 1 shows that in March, due to limited development of the trees' leaves, there was the lowest photosynthetic capacity of the orchard (lower value of b₁). The highest value was observed in April, because the trees already had complete leaf development, with sunny days (slight cloudiness) and moderate temperatures. From May to July, the peak photosynthetic capacity of the orchard was very similar, and decreased in August and September. The daytime respiration rate (parameter b₃ of the rectangular hyperbolic equation) (Table 1) was lower and approximately the same during March, April, and May. The peak rate of daytime respiration was observed in September (Table 1), probably due to the onset of leaf senescence. At this stage, new leaves are no longer produced, and the photosynthetic capacity of the leaves is reduced. Previous studies in controlled environments with Sunflower (*Helianthus annuus*), Lily (*Lilium candidum*), Maize (*Zea mays*), and Alfalfa (*Medicago sativa*) plants have also shown that the relationship between the net photosynthesis rate and the PAR rate can be described using a rectangular hyperbolic function (Sun and Wang, 2018). The relationship between NEE and PAR in young rubber trees (*Hevea brasiliensis* Müll. Arg.) was described using a rectangular hyperbolic function. The NEE was up to -4.94 μmol/m²/s (Chayawat et al., 2019). Studies conducted by Zhang et al. (2015) in a maize crop observed a direct proportional relationship between the PAR rate and the NEE rate.

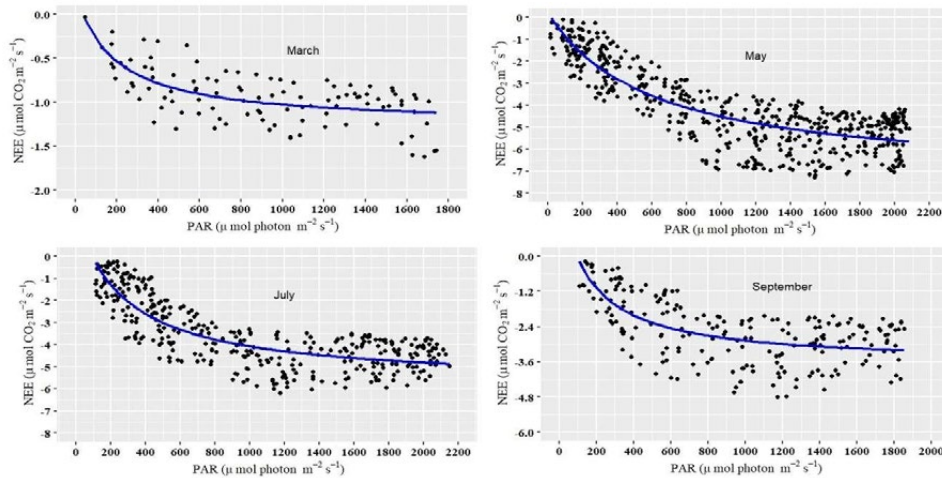


Fig. 3: Relationship between CO₂ net ecosystem exchange (NEE) and the photosynthetically active radiation (PAR) absorbed by the tree canopy of a seven-year-old pecan nut orchard in northern Mexico. The points represent the observed data, and the line corresponds to the adjusted NEE values with a rectangular hyperbolic function.

Table 1: Parameters of the rectangular hyperbolic function and coefficient of determination (r²) in the growth months of a seven-year-old pecan nut orchard from northern Mexico.

Month	b1 (µmol CO ₂ /m ² /s)	b2 (µmol photons/m ² /s)	b3 (µmol CO ₂ /m ² /s)	r ²
March	-1.504	188.748	0.238	0.425
April	-8.58	942.610	0.223	0.805
May	-7.558	602.669	0.204	0.733
Jun	-7.258	246.215	1.306	0.512
July	-7.633	282.216	1.876	0.693
August	-5.350	204.500	1.387	0.339
September	-5.963	153.847	2.295	0.426

Quantum yield and quantum efficiency of orchard trees

Of the months evaluated, the quantum yield (expressed in mmol CO₂ fixed per mmol of photons absorbed (mmol CO₂/mmol photons)) in March showed the lowest yield (1.328) (Table 2), which was because the trees were beginning their leaf development, and the photosynthetic activity was small. The highest quantum yield was in May (4.870) and June (4.421), due to higher leaf development and the greater photosynthetic capacity of the leaves. The CO₂ assimilation rate decreased in August and September (Table 2), thereby reducing the orchard trees' quantum yield. A similar pattern was observed in the quantum efficiency, which represents the ratio of the energy used for CO₂ assimilation to the energy contained in the PAR absorbed by the canopy trees. The lowest quantum efficiency was observed in March

(0.286 %) due to the lower leaf area of the trees. The highest quantum efficiency was observed in May (1.049 %) and June (0.952 %) (Table 2), which was due to greater leaf area and the greater photosynthetic capacity of the leaves. In August and September, the leaves began to lose their photosynthetic capacity, and their quantum efficiency decreased (Table 2). The observed quantum yield values are small, meaning that only a small proportion of the absorbed PAR is used for CO₂ assimilation. The rest of the PAR absorbed only causes thermal effects, which the trees must dissipate through high rates of foliar transpiration. As the quantum yield values of this study were obtained at the orchard level, and the tree's canopy only covered 16.4 % of the total surface, they were small compared to the values of previous studies, which were obtained at the leaf level. For example, Lombardini et al. (2009) reported that from June to August, Pawnee pecan

Net assimilation exchange of pecan trees

Table 2.: Average daily values per month of the quantum yield and quantum efficiency of a 7-year-old pecan nut orchard from Northern Mexico

Months	Quantum yield ($\mu\text{mol CO}_2/\text{mmol photons}$)	Quantum efficiency (%)
March	1.328 ^d	0.286 ^d
April	4.231 ^b	0.911 ^b
May	4.870 ^a	1.049 ^a
Jun	4.421 ^{ab}	0.952 ^{ab}
July	4.167 ^b	0.897 ^b
August	2.946 ^c	0.634 ^c
September	3.317 ^c	0.714 ^c

Means with different letters within the columns are different (Tukey, $\alpha \leq 0.05$)

Table 3: Integrated daytime and night-time NEE values of a pecan nut orchard (of 7 years old), during the growth months, and net assimilation retention (NAR)

Month	Daytime NEE (mmol/m^2)	Night-time NEE (mmol/m^2)	NAR (mmol/m^2)
March	398.05	689.47	1 087.52
April	-5 112.18	1 094.65	-4 017.53
May	-5 717.95	1 146.75	-4 571.20
Jun	-4 611.47	1 029.02	-3 582.45
July	-4 175.12	1 646.06	-2 529.06
August	-3 591.24	1 529.83	-2 061.41
September	-2 969.64	1 368.83	-1 600.81

trees' leaves highest quantum yield under direct solar radiation was around $12.5 \mu\text{mol}/\text{mmol}$, and for the Stuart cultivar, for the same conditions, it was around $10 \mu\text{mol}/\text{mmol}$. The quantum yield values of this study were also small compared to the values reported for plant ecosystems wherein the plant canopy covers the entire surface. In a forest ecosystem composed of a mixed patchy coniferous/deciduous forest located in Belgium, the quantum yield was $44 \mu\text{mol}/\text{mmol}$ (Carrara *et al.*, 2004). For a plantation of young rubber trees (*Hevea brasiliensis* Müll. Arg.), the quantum yield was $42.8 \mu\text{mol}/\text{mol}$ (Chayawat *et al.*, 2019). The quantum yield values observed in a vineyard (*Vitis vinifera* L.) in July ($5.456 \mu\text{mol}/\text{mmol}$) and August (4.118) (Zermeño-Gonzalez *et al.*, 2021) were similar to the values obtained in this study in May (4.870) and June (4.421).

Monthly balance of the CO_2 net ecosystem exchange

Because the orchard was made up of young trees (of 7 years old), most of the surface was bare soil or soil with little native vegetation, since the area of the tree's crown was only 16.4% of the total area. In March, the trees in the orchard were beginning to develop their leaf area, so most of the surface was bare soil, in such a way that the integrated daytime CO_2 NEE for the entire month resulted in a positive value of 398.05 millimoles

per square meter (mmol/m^2), indicating that during daytime, the release of CO_2 was more significant than the assimilation (Table 3). For the months evaluated, the integrated night-time CO_2 NEE was positive, because at night, CO_2 release only occurs due to the nocturnal respiration of the vegetation and the soil surface (Table 3). For the months after March, the integrated daytime CO_2 NEE was negative, indicating a higher rate of CO_2 assimilation than of release. The highest integrated daytime CO_2 NEE was observed in May ($-5 112.18 \text{ mmol}/\text{m}^2$), when the trees were in the most active stage of growth and fruit development; the trees allocated more photosynthates to fruit development, and fewer to wood growth (López and Arreola, 2008). The highest night-time CO_2 NEE was observed in July ($1 646.06 \text{ mmol}/\text{m}^2$), which was probably due to the higher night-time temperature of the trees' leaves and soil, which increased the respiration rate of the soil-vegetation ecosystem (Flanagan and Johnson, 2005; Xu *et al.*, 2004). The pecan nut orchard's net CO_2 assimilation retention (NAR) was the difference between daytime and night-time CO_2 NEE. From March to September, the NAR was $-17 274.94 \text{ mmol}/\text{m}^2$. April and May had the higher NAR with $-4 017.53 \text{ mmol}/\text{m}^2$ and $-4 571.20 \text{ mmol}/\text{m}^2$, respectively (Table 3). Considering that 46.4 % of the net assimilation of CO_2 is destined for the growth

and formation of wood (Wang *et al.*, 2007, Negi *et al.*, 2003), this corresponds to 8 015.57 mmol/m², which equals 80 155.72 mol CO₂/ha, and corresponds to 0.962 t C/ha retained in the wood of the trees' orchard for the mentioned months. This value is lower than that observed by Wang *et al.* (2007) in pecan nut trees (Western Schley) of 12 m tall, wherein the total soil surface was shaded by the trees' canopy (10.24 t C/ha/y) in Las Cruces, N.M, USA. In pecan nut (*Carya illinoensis* (Wangenh.) K. Koch) trees of 11 years old in a high-density plantation, the orchard carbon stock was 22.8 t C/ha, and the carbon assimilation rate was 1.67 t C/ha/y (Yadav *et al.*, 2017). The atmospheric CO₂ assimilation values obtained in this study are small compared to those reported in other pecan walnut orchards and other woody tree species, because the trees were small and only covered 16.4% of the total area. However, during a large proportion of the growth months, carbon dioxide's assimilation is greater than its release, demonstrating that young pecan nut orchards, besides their economic and social importance, can also ecologically participate in the sequestration of atmospheric carbon to mitigate global warming. The peak daily values of NEE are observed around noon, and the peak monthly net CO₂ assimilation is from April to July. The main environmental factors contributing to these peaks are the incident solar photosynthetically active radiation, air temperature, relative humidity, and wind speed. In addition to exchanging CO₂ with the atmosphere, pecan nut trees and other plant ecosystems also exchange water vapor, oxygen, and other atmospheric gases. However, the scope of this study was only on the CO₂ exchange between the pecan nut orchard and the atmosphere. The potential limitations that may affect the CO₂ assimilation of a young pecan nut orchard are possible plant diseases that affect the leaves' growth, and adverse weather conditions that induce stomatal closure.

CONCLUSION

The rate of assimilation and the release of CO₂ from the pecan nut trees depends on the growth month. In March, the trees are just beginning their leaf development, and the orchard is a source of CO₂ released during daytime and night-time. The orchard is a sink for atmospheric CO₂ from April to September. The highest daytime CO₂ NEE assimilation rate corresponded to the peak rate of photosynthetically active radiation (PAR) absorption by the trees' canopy. It

was observed between 11:00 and 14:00 during the day, throughout the growth months of the trees. The rate of assimilation being greater than the rate of release is attributable to the formation of carbon compounds that can be used for wood growth and fruit development. The CO₂ net ecosystem exchange values observed in this study are small, because the orchard was made up of young trees (of 7 years old) that had an average crown diameter of 4.78 m, which is equivalent to an area of only 15.75 m². This crown surface only covered 16.4% of the total soil surface. The relationship between the CO₂ net ecosystem exchange and the photosynthetically active radiation (PAR) absorbed by the trees' canopy (an average of 30 min) through the growth months was described using a rectangular hyperbolic function. This function depicts an increase in NEE as the absorbed PAR increases. The orchard's highest yield and quantum efficiency were observed in May, the month with the highest net assimilation of CO₂. Despite the young age of the trees, the orchard has a retention capacity of 0.962 t C/ha for the months evaluated. The orchard sequestration capacity will increase with the growth of the trees due to a greater total leaf area and greater biomass development. Therefore, due to their condition of woody and long-living plant species, pecan nut trees, in addition to their use for walnut production, may play an essential role in CO₂ assimilation and atmospheric carbon sequestration, thereby significantly contributing to society.

AUTHOR CONTRIBUTIONS

A Zermeño-González performed the experimental design, analysis, and interpretation of the data, and prepared the manuscript. E. Jiménez-Alcala participated in the field study, data collection, and literature review. J. Gil-Marín contributed to the literature review, manuscript preparation, and editing. H. Ramírez helped in the literature review and manuscript preparation. M. Cadena assisted in the field study, data collection, and analysis. A. Melendres contributed to the field study, sensor calibration and operation, and data collection.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, no ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, or redundancy, have been observed by the authors.

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ABBREVIATIONS

α	Alpha
%	Percent
$\Delta\rho\text{CO}_2$	Change of density of carbon dioxide
Δt	Time segment
Δz	Height above the ground surface
$\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Micromoles of carbon dioxide per square meter per second
$\mu\text{mol photon}/\text{m}^2/\text{s}$	Micromoles of photons per square meter per second
$\mu\text{mol CO}_2/\text{mmol photon}$	Micromoles of CO_2 per mmol of photons
ρCO_2	Density of carbon dioxide
3-D	Three-dimensional
$b1$	Highest photosynthetic capacity of the ecosystem

$b2$	Photosynthetically active radiation of the mean value of the photosynthesis rate
$b3$	Daytime respiration rate of the ecosystem
CO_2	Carbon dioxide
cm	Centimeter
$^\circ\text{C}$	Degrees Celsius
E	Energy
FCO_2	Carbon dioxide flux
ha	Hectare
H_2O	Water
Hz	Hertz
LPH	Liters per hour
m	Meter
masl	Meters above sea level
mmol/m^2	Milimol per square meter
min	Minutes
MJ	10^6 joules
m/s	Meter per second (velocity unit)
m^2	Meter square
NEE	Net ecosystem exchange
nm	Nanometer
PAR	Photosynthetically active radiation
$\text{Quant}_{\text{yield}}$	Quantum yield
$\text{Quant}_{\text{Eff}}$	Quantum efficiency
s	Second
t	Ton
t/ha	Tons per hectare
TC/ha	Tons of carbon per hectare
$\text{t}/\text{CO}_2/ha/y$	Tons per carbon dioxide per hectare per year
w	Vertical wind speed

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