Article

Net carbon dioxide exchange rate of a vineyard during the growth cycle

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Abstract

In addition to harvesting of grape for fresh consumption, juice making and wine production, vineyards (*Vitis vinifera* L.) for their status as woody and long-lived plants can have an important participation in the assimilation and retention of atmospheric carbon. The objective of this study was to evaluate the net carbon dioxide exchange rate of the ecosystem (NEE) in a vineyard during its production cycle, and its relationship to atmospheric carbon sequestration. The study was carried out (from April to December 2018) in an 11-year-old Shiraz cultivar vineyard in the Vinícola San Lorenzo, Parras, Coahuila. The rate of carbon dioxide flow between the vineyard canopy and the atmosphere, through the months of growth was measured with the sensors of an eddy covariance system. From April to November the vineyard acts as an atmospheric carbon sink and during May, June and July the highest NEE values were obtained, with an average value of -3.014 g C m^{-2} s^{-1}. The carbon stored in the wood of the vineyard plants was 3.35 t C ha^{-1}. These results show that vineyards are agricultural systems that can have a significant role in mitigating atmospheric carbon dioxide, which, coupled with their status as woody-long-lived plants and the large established areas of vineyards in Mexico and the world, are very important carbon storage ecosystems.

Keywords: *Viits vinifera* L., carbon sequestration, photosynthesis, photosynthetically active radiation.

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Introduction

The vine (*Vitis vinifera* L.) is a woody climbing plant whose fruit is the grape with which the wines are made, is native to Asia and is known since prehistory. The Spaniards introduced this crop to North America (Vinetur, 2017). In Mexico, the planting of vines for the production of wine began in 1597 in Valle de Parras, in Hacienda San Lorenzo (CMV, 2018). Currently, grape production for wine reaches 6 474 ha, where Baja California concentrates the highest percentage of production with 57% of the total of the 11 producing states (SADER, 2018). In 2019, the vineyards global area, including all production orientations, was 7.402 million ha. Spain has the largest area (966 000 ha), followed by China and France with 855 000 and 749 000 ha (OIV, 2019).

In Mexico, the vineyards bring together 2 900 producers, who generate more than 3 000 jobs directly and indirectly and more than 500 thousand agricultural day laborers are involved in support of pruning and harvesting activities (El financiero, 2018). In addition to the economic and social importance of the vine, vineyards can have an important participation in the assimilation and retention of atmospheric carbon, as they are woody and long-lived plants that can be in production for more than 40 years.

Vine has an average life of approximately 50 years, although some vines can live up to 100 years (Cano, 2015; Domínguez de la Iglesia; 2018). The net carbon dioxide exchange rate (NEE) represents the CO_2 assimilation capacity of a plant area, which depends on the type of vegetation, growth status, climatic conditions and soil moisture.

Several studies have reported NEE of different types of forests and localities (Carrara *et al*., 2003; Desai *et al*., 2005; Yi *et al*., 2008). In different fruit orchards (Testi *et al*., 2008; Martin-Gorriz *et al*., 2011; Zanotelli *et al*., 2013). And in different varieties of vineyards (Nardino, *et al*., 2007; Smart *et al*., 2009; Vendrame, 2016). Daily, monthly or per growth cycle integrated values of NEE (mol m^{-2}) may indicate the assimilation capacity of atmospheric carbon dioxide in a given plant ecosystem. Previous studies have evaluated the rate of fixation of carbon dioxide of vineyards of different cultivars and various ages (Guo *et al*., 2014; Pitacco and Meggio, 2016).

Assimilated carbon that integrates into wood growth is defined as carbon sequestration. It depends on the type of plant ecosystem, climatic conditions and soil moisture. Because of their longevity and accumulated biomass volume, forests in favorable climatic conditions have high carbon sequestration potential (Nowak and Crane, 2002; Pimienta de la Torre *et al*., 2007; Rodríguez-Larramendi *et al*., 2016).

Unlike forests, vineyards have a much lower volume of accumulated biomass, but under good agronomic management, the annual carbon sequestration rate may be high (Vendrame, 2016; Brunori *et al*., 2016). As woody and long-lived plants, vineyards fix and retain some of the carbon dioxide assimilated for wood growth, so they can have a significant contribution in atmospheric carbon sequestration.

Therefore, the objective of this study was to determine the NEE of a vineyard (*cv* Shiraz), its variation through the months of growth and its relationship to atmospheric carbon sequestration.

Materials and methods

Location and features of the study site

The study was carried out during the production cycle from April to December 2018 in a 11-year-old *cv* Shiraz vineyard, owned by the Vinícola San Lorenzo, Parras de la Fuente, Coahuila, Mexico (25° 26° north latitude, 102° 10° longitude west, at 1 500 masl) with dry semi-warm climate, with average annual temperature of 15 to 20°C, average annual precipitation of 374.2 mm and evaporation rate of 2 118 mm (CONAGUA, 2017). The study was carried out in lot 32 corresponding to an area of 6.37 ha of *cv* Shiraz, with 1.5 m distance between plants and 2.5 m between rows (2 666 plants ha^{-1}). The vineyard received agronomic management (fertilization, pruning, irrigation and phytosanitary control) according to the protocols established by the Vinícola.

Instrumentation and measurements

The eddy covariance method was used to measure the NEE between the vineyard canopy and the atmosphere according to the following equations (Martens *et al*., 2004): $NEE=FCO_2+\frac{\Delta\rho CO_2}{\Delta t}*\Delta z$ 1), where FCO_2 is the CO_2 flow, $\Delta\rho CO_2$ is the change in the density of CO_2 in a given time segment Δt (30 min) and Δz is the height (3 m above the ground surface) at which the measurements were made. FCO_2 was obtained with the following relationship: $FCO_2=\overline{w'*\rho CO_2'}$ 2). Where: w is the vertical wind speed, ρCO_2 is the density of carbon dioxide. Variables with prime symbol mean deviations from the mean, and the bar over two variables denotes the covariance between the variables for a given time segment (30 min).

The sensors of the eddy system for measurements of CO_2 flows were placed on a pole 3 m high (1.2 m above the canopy of the vineyard) (Figure 1). Sonic temperature was measured with a three-dimensional sonic anemometer (CSI-CSAT3, Campbell, Scientific, Inc., Logan, Utah, USA); to obtain ρCO_2 an infrared analyzer of carbon dioxide and open path water vapor (Open Path CO_2/H_2O analyzer, LI- 7500, LI-COR, Lincon, Nebraska, USA) were used.

Sensors were connected to a CR1000 datalogger (Campbell, Sci., Inc, Logan, Utah, USA) to perform measurements at a frequency of 10 Hz and generate averages of 30 min. CO_2 retention of the vineyard (mmol m^{-2}) was obtained by integrating the NEE (average of 30 min) diurnal (negative values), while the release rate was the integration of the nocturnal NEE rate (positive values). Net CO_2 retention was the difference in integrated diurnal and nocturnal values.

The photosynthetically active radiation rate (PAR) absorbed was obtained by placing two quantum sensors (model SQ-512, Apogge Inst., Logan, Utah, USA) one meter above the canopy of plants, one facing the midpoint of the canopy and the other towards the zenith. The difference between the incident PAR and the reflected PAR corresponded to the PAR absorbed by the canopy of the vineyard (PAR_{abs}). Measurements were made at a frequency of one Hz and 30 min averages, connecting the sensors to another CR1000 datalogger.

Figure 1. Sensors of an eddy system for measuring the flow of carbon dioxide between the canopy of the vineyard and the atmosphere. Production cycle 2018. Vinícola San Lorenzo, Parras, Coahuila, Mexico.

The carbon stored in the vineyard plants was determined by measuring the diameter and length of the trunk and the branches of five plants of the vineyard (since the plants are very uniform). The average volume of wood per plant was multiplied by the number of plants per hectare (2 666) to obtain the total volume of wood per ha. The total weight of the wood was obtained considering a wood density of 0.701 g cm^{-3} (Nasser *et al.*,2014). The stored carbon was obtained assuming that 45% of the composition of the dry matter corresponds to carbon (Yerena-Yamallel *et al*., 2012).

Results and discussion

Instantaneous rate of net carbon dioxide exchange

The maximum instantaneous rate (30 min average) of diurnal net carbon dioxide exchange (NEE) through the vineyard growth months (April to December), was observed at around 12:00 h of the day (Figure 2 and 3). In the same figures it is also observed that the diurnal NEE has the same pattern of variation as the PAR-abs by the canopy of the vineyard, but with the opposite sign (since the flow of CO_2 towards the canopy is set to negative). Note that the maximum PAR-abs also occurs at around 12:00 h and is very sensitive to changes in cloudiness conditions (Figure 2 and 3) as well as NEE, but to a lesser extent. Between April and August, the maximum instantaneous rate of NEE occurred, where May and June had the highest values (up to -9 mol $m\mu^{-2}$ s^{-1}).

From September to December there was a progressive reduction in the NEE rate (Figure 3). Previous studies in this crop and other plant areas have shown similar relationships. For example, Wofsy *et al*. (1993) noted that the NEE rate is systematically increased with the incidence of PAR in a middle latitude forest, the higher NEE values were also observed around 12:00 h and during July the NEE was higher.

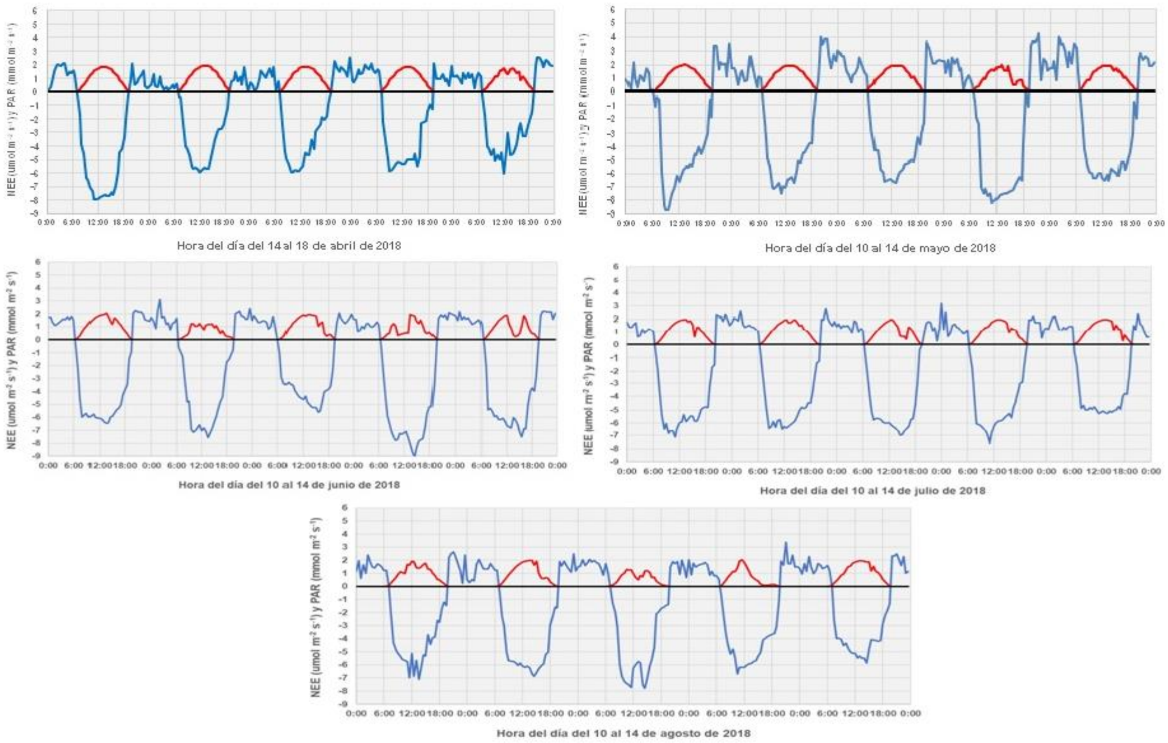

Figure 2. Net carbon dioxide exchange rate (NEE) (blue lines) averages of 30 min and photosynthetically active radiation assimilation (PAR) (red lines) absorbed by the canopy of the vineyard, during the months of April to August 2018, in Vinícola San Lorenzo, Parras, Coahuila, Mexico.

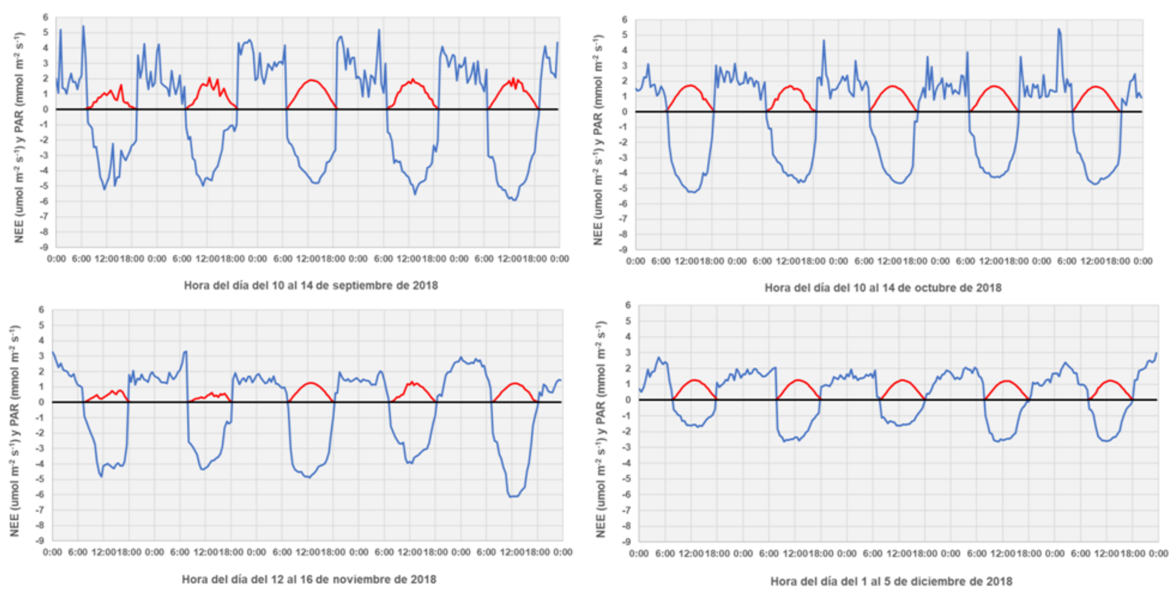

Figure 3. Net carbon dioxide exchange rate (NEE) (blue lines) averages of 30 min and photosynthetically active radiation assimilation (PAR) (red lines) absorbed by the canopy of the vineyard, during the months of September to December 2018, in Vinícola San Lorenzo, Parras, Coahuila, Mexico.

Similar to the results observed in this study, in a vineyard in arid northwest China, the hourly rate of NEE was positive (CO_2 release) at the beginning of the production cycle, high negative values (assimilation) in the middle stage of the production cycle and small negative values at the end of the vineyard cycle (Guo *et al*., 2014).

Other vineyard studies of different cultivars and ages have reported NEE rates similar to those observed in this study. For example, in a table grape vineyard of Regina cultivar, during the summer in southern Italy, the maximum NEE rate was -5 to -11 μmol m^{-2} s^{-1} (the negative sign indicates assimilation) (Nardino *et al*., 2007). In a 7-year-old Cabernet Sauvignon, from California, USA, during the summer it was up to -13 μmol m^{-2} s^{-2} (Smart *et al*., 2009), for the *cv* Sauvignon Blanc, during June in Portogruaro located in northern Italy, the NEE was up to -15 μmol m^{-2} s^{-1}, (Vendrame, 2016).

Net integrated exchange rate of carbon dioxide from the vineyard

The values of the instantaneous rate (average of 30 min) of net exchange of carbon dioxide were separately integrated for diurnal (negative) and nocturnal conditions (positive values) in the vineyard growth months (April to December) (Table 1). The difference in integrated diurnal and nocturnal values represents the carbon that is fixed to produce carbon compounds (Meggio and Pitacco, 2016; Zanotelli *et al*., 2018).

Table 1. Monthly daily average of net carbon dioxide exchange rate (NEE), diurnal and nocturnal, and monthly daily balance. Vinícola San Lorenzo, production cycle 2018. Parras, Coahuila, Mexico.

Month	NEE diurnal (mmol m^{-2} d^{-1})	NEE nocturnal (mmol m^{-2} d^{-1})	NEE net (mmol m^{-2} d^{-1})
April	-215.647	63.882	-151.765
May	-265.71	66.258	-199.452
June	-258.261	60.483	-197.77
July	-229.645	51.097	-178.548
August	-195.903	68.516	-127.387
September	-163.033	94.433	-68.6
October	-151	89.214	-61.786
November	-120.964	73.179	-47.786
December	-53.2	65.8	12.6

From April to August, the largest diurnal NEE was observed, where May and June had the highest values (Table 1). A progressive reduction in the daily diurnal rate of NEE was observed from September to December; while from August to November, the highest values of nocturnal NEE (CO_2 release) were observed. The net balance of monthly daily average of NEE (difference between diurnal and nocturnal NEE) was higher from April to August, with higher values in May and June (Table 1).

The lower net balance values of NEE were from September to December with a progressive decline. In December, the net balance was positive, indicating that the vineyard behaved as a source of release of CO_2 into the atmosphere. The average of diurnal NEE for the months of May, June and July (months of greatest assimilation) was 251.205 mmol m^{-2} d^{-1} (Table 1), which corresponds to -3.014 g C m^{-2} d^{-1}. For a table grape vineyard, the diurnal NEE average was -2.079 g C m^{-2} d^{-1} (Nardino *et al*., 2007), while, for a vineyard of the Merlot cultivar, the diurnal NEE at the fruit growth stage was up to -9 g C m^{-2} d^{-1} (Guo *et al*., 2014).

In another study, Pitacco and Meggio (2016) reported that the daily average of NEE of the production cycle of a *cv* Carmenere vineyard was -2.33 g C m^{-2} d^{-1}. The above data show that, vineyards can have a significant role in mitigating atmospheric carbon dioxide, as they are woody plants and can be in production for up to 40 years.

Carbon stored in the vineyard

The average carbon content per vineyard plant was 1.258 kg (Table 2), with a coefficient of variation of 11.62%, indicating that the vineyard plants are very uniform and that the sample of five plants was suitable for determining the carbon content in plants. For a density of 2 666 plants ha^{-1}, it is equal to 3.35 t C ha^{-1} stored in the wood of the vineyard. Other studies have reported similar values to what was found in this study.

Table 2. Wood volume of five 11-year-old vine plants (*cv* Shiraz), dry weight and corresponding carbon content. Vinícola San Lorenzo, Parras, Coahuila.

Plant	Wood volume (cm^3)	Dry weight of wood (kg)	Carbon content (kg)
1	3 821.37	2.678	1.205
2	3 575.84	2.506	1.128
3	4 464.78	3.129	1.408
4	3 578.94	2.508	1.129
5	4 505.63	3.158	1.421
Average	3 989.314	2.796	1.258

For example, Williams *et al.* (2011) point out that the average carbon stored in the plants of five vine cultivars in the state of California, USA was 3 t $ha^{-1.}$ Studies that were carried out in vine plants of the Sauvignon cultivar in Sacramento California, USA showed that the carbon stored in wood is 4.8 t ha^{-1} (Morandé *et al.*,2017). In the central part of Italy in a vineyard of the Merlot cultivar, the carbon retained in wood was 2.28 t ha^{-1} (Brunori *et al*., 2016).

These results show that, in addition to the economic and social importance of vineyards, they are also agricultural ecosystems, which have a significant contribution in the sequestration of atmospheric carbon, which is due to their status as woody and long-lived plants and the area established in both Mexico (32 000 ha) (Boullosa, 2017), and globally (7.4 million ha) (OIV, 2019).

Quantum efficiency of the vineyard

The quantum efficiency of the vineyard (relationship between CO_2 millimoles assimilated per mol of photons absorbed by the canopy) during the months of the production cycle (April to December) was very similar with very little variation between the different months (Table 3). The lowest value was 4.118 mmol mol^{-1} in August and the highest 5. 456 mmol mol^{-1} in June. The average value of the months of the production cycle was 4.25 mmol mol^{-1} with a small coefficient of variation of 8.99%. The uniformity of the quantum efficiency of the vineyard is an indicator of the good agronomic management of the vineyard and the adequate and uniform irrigation of the plants during the growing months.

Table 3. Net diurnal carbon dioxide exchange (diurnal NEE), photosynthetically active absorbed radiation (PAR_abs) and monthly daily average of quantum efficiency (Ef quántica) of the vineyard during the months of the production cycle 2018. Vinícola San Lorenzo, Parras, Coahuila, Mexico.

Month	NEE diurno (mmol m^{-2})	PAR_abs (mol m^{-2})	Ef quántica (mmol mol^{-1})
April	-215.647	47.558	4.534
May	-265.71	51.499	5.16
June	-258.261	47.333	5.456
July	-229.645	47.159	4.87
August	-195.903	47.57	4.118
September	-163.033	34.306	4.752
October	-151	32.15	4.696
November	-120.964	26.614	4.541
December	-53.2	12.6	4.222

The quantum efficiency values observed in this study are lower than those reported in previous studies, and it is because, in this study, measurements were made at canopy scale with daily integrated values (8:00 to 19:00 h), where a wide range of temperature, humidity and radiation variations are available; while previous studies report foliar measurement efficiencies in short times (about one minute), with controlled conditions of the above variables. For example, foliar measurements of the photosynthesis rate of mature vine plant leaves from the Riesling and Chasselas cultivars at a temperature of 25 to 30°C and a PAR incidence of 1 000 µmol m^{-2} s^{-1} were 12.66 µmol CO_2 m^{-2} s^{-1}, which corresponds to a quantum yield of 12.66 mmol mol^{-1} (Zufferey *et al*., 2000).

Similarly, the maximum rate of foliar photosynthesis of Semillon *cv* vine plants, at a temperature between 25 and 30 °C and a PAR of 1000 µmol m^{-2} s^{-1}, was 16.25 µmol CO_2 m^{-2} s^{-1}, which corresponded to a quantum efficiency of 16.25 mmol mol^{-1} (Greer and Weedon, 2012). The maximum photosynthesis rate of vine leaves of the *cv* Chardoney and Merlot for a temperature of 25 °C, a carbon concentration of 400 µmol mol^{-1}, a PAR incidence of 600 µmol m^{-2} s^{-1} was 8.5 µmol CO_2 m^{-2} s^{-1}, which corresponded to a quantum efficiency of 14.16 mmol mol^{-1} (Greer, 2017).

Conclusions

The maximum NEE (averages of 30 min), through the months of the production cycle (April to December) was observed around noon and in May and June the highest values are presented. The NEE follows the same pattern of variation as PAR absorbed by the vineyard canopy. From April to November, the average daily monthly diurnal rate was higher than the diurnal, indicating that the vineyard was a sink for atmospheric carbon. As of December, due to the senescence and fall of the leaves, the nocturnal NEE was greater than the diurnal and the vineyard was a source of CO_2 release.

Due to the carbon stored, the annual carbon sequestration rate and the large areas established in Mexico and the world, vineyards are agricultural systems of importance for the assimilation and retention of atmospheric carbon. The average daily quantum yield of the vineyard was very stable through the months of the vineyard growth cycle, which is due to good agronomic management of the crop and the timely application of irrigation.

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