

Estimated carbon dioxide exchange for three native species in an ecological reserve of Mexico City

ERIKA SÁNCHEZ-LEÓN, TELMA CASTRO, ÓSCAR PERALTA, HARRY ÁLVAREZ-OSPINA,
MARÍA DE LA LUZ ESPINOSA and AMPARO MARTÍNEZ-ARROYO

Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica s/n, Ciudad Universitaria, 04510 Ciudad de México, México

Corresponding author: Erika Sánchez-León; email: erikas@atmosfera.unam.mx

Received: December 10, 2015; accepted: May 11, 2016

RESUMEN

Se estimó la captura y emisión de CO₂ de tres especies (*Buddleia cordata*, *Senecio praecox* y *Echeveria gibbiflora*) en la Reserva Ecológica del Pedregal de San Ángel. El muestreo se realizó durante los meses de febrero, marzo, abril y noviembre (temporada seca) y de julio a octubre (temporada de lluvias) en 2010. En la temporada seca *B. cordata* y *S. praecox* capturaron 16.14 y 3.25 kg de CO₂, respectivamente, en tanto que *E. gibbiflora* emitió 45.76 kg de CO₂. En la temporada de lluvias el intercambio de CO₂ fue diferente para las tres especies. La tasa de fotosíntesis durante la temporada seca y de lluvias fue respectivamente de 22 y 6 μmol CO₂ m⁻² s⁻¹ para *B. cordata*, 27 y 5.25 μmol CO₂ m⁻² s⁻¹ para *S. praecox*, y 29 y 3 μmol CO₂ m⁻² s⁻¹ para *E. gibbiflora*. Adicionalmente, se estimó el índice de vegetación de diferencia normalizada con datos de MODIS. Los resultados indican que la intensidad del verdor en el sitio aumentó durante los meses de lluvia. En este trabajo se explica la contribución de dichas plantas al ciclo de carbono en un ecosistema ubicado dentro de una zona urbana, así como la relación de variables ambientales como temperatura, densidad del flujo fotosintético de fotones y humedad relativa en la captura o emisión de CO₂. Este trabajo proporciona información sobre la dinámica del ciclo del carbono en ecosistemas urbanos, lo cual puede ser útil para estudios futuros sobre la mitigación del cambio climático.

ABSTRACT

Capture and emission of carbon dioxide of three species (*Buddleia cordata*, *Senecio praecox* and *Echeveria gibbiflora*) in the Reserva Ecológica del Pedregal de San Ángel (Ecological Reserve of the Pedregal de San Ángel), were estimated. CO₂ sampling was carried out in 2010 during the dry (February, March, April and November) and rainy seasons (July to October). On the dry season *B. cordata* and *S. praecox* captured 16.14 and 3.25 kg CO₂, respectively, whereas *E. gibbiflora* emitted 45.76 kg CO₂. In the rainy season the exchange of CO₂ was different for the three species. In the dry season, the photosynthetic rate was 22 μmol CO₂ m⁻² s⁻¹ for *B. cordata*, 27 μmolCO₂ m⁻² s⁻¹ for *S. praecox* and 29 μmolCO₂ m⁻² s⁻¹ for *E. gibbiflora*. In the rainy season they were 6, 5.25 and 3 μmol CO₂ m⁻² s⁻¹, respectively. In addition, MODIS data were used to estimate the normalized difference vegetation index (NDVI), indicating that the intensity of greenery at the site increased during the rainy months. This paper explains the contribution of studied plants to the carbon cycle of an ecosystem located within an urban area, and the relationship of environmental variables such as temperature, density photosynthetic photon flux and relative humidity in the capture or emission of CO₂. This work provides valuable information about the carbon cycle dynamics on urban ecosystems, which can be useful in future studies for climate change mitigation.

Keywords: Photosynthesis, *Buddleia cordata*, *Senecio praecox*, *Echeveria gibbiflora*, capture and emission CO₂, Mexico City.

1. Introduction

The global warming phenomenon, which is caused by emissions of greenhouse gases (GHGs) that contribute to an increase in earth surface temperature, is presented nowadays as a problem for the development of life on earth. Carbon dioxide (CO₂) is one of the gases that most favors the heating process, and its concentration has increased in recent years mainly due to anthropogenic activities, going from 280 ppm in pre-industrial times to 398.72 ppm in 2014 (IPCC, 2007; NOAA, 2014). According to the national inventory of GHGs of Mexico, the total CO₂ emissions were 493.45 Mt in 2010, contributing with 65.9% to the total inventory and having an increase of 23.6 % compared to 1990 (INE, 2010).

There are various carbon sinks in the world that have been associated to an important contribution of forests, which are responsible for 60% of the net sequestration of carbon dioxide (Nobel, 2009). It is estimated that the world's forests capture over 650 Mt of carbon, which helps to mitigate climate change and preserve biodiversity (FAO, 2010). However, not only forests sequester CO₂; it has been shown in several studies that the presence of trees in urban areas favors the reduction of some air pollutants and contributes to carbon sequestration (Yang *et al.*, 2005; Kordowski and Kuttler, 2010; Velasco *et al.*, 2013). There are several techniques for estimating carbon sequestration; one of them is through the use of technologies such as satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS), whose purpose is to model carbon and water cycles globally. Furthermore, MODIS allows measuring ecosystem's primary productivity, vegetation indices and other environmental variables (Zhao *et al.*, 2005).

The captured carbon is also estimated using different models, which evaluate photosynthetic and environmental parameters (Kim and Lieth, 2003; Schultz 2003; Xu and Baldocchi, 2003; Sharkey *et al.*, 2007), whereas others evaluate the carbon balance between plants and the atmosphere (Harnos *et al.*, 2006). Several experimental studies of photosynthesis use CO₂ analyzers and measurements in situ (Myers *et al.*, 1999; Long and Bernacchi, 2003; Kitao *et al.*, 2007). However, few studies have evaluated the importance of individual species concerning their contribution to CO₂ capture and emission in the environment. This information

provides knowledge over the role of vegetation. Urban forests can contribute significantly to the reduction of air pollution by relieving the intensity of the heat island (Yang *et al.*, 2005). Velasco *et al.* (2013) mentioned that vegetation in an urban area contributes to the capture of CO₂ during the day and promotes local air cooling due to transpiration, serving as an alternative mitigation for climate change.

In this study our objective was to estimate CO₂ capture and emission through the photosynthetic rate of three endemic plants (*E. gibbiflora*, *B. cordata*, and *S. praecox*) and the relationship between temperature (T), density photosynthetic photon flux (DPPF), and relative humidity (RH) in dry and rainy seasons at the Reserva Ecológica del Pedregal de San Ángel (Ecological Reserve of the Pedregal de San Ángel, REPSA); we also estimated the contribution to the carbon cycle to understand the role of urban plant ecosystems in climate change mitigation. This site was chosen because it is one of the few protected natural reserves located in a megacity; moreover, it is of great value for the conservation of biodiversity and it provides environmental services to the south of the metropolitan area of Mexico City. It also has a special ecosystem, a xerophilus shrubland settled into a basaltic substrate whose soils are scarce and shallow (Rzedowski, 1954), which is the reason why this work is focused on the aboveground biomass. The carbon cycle in vegetation starts with CO₂ fixation mainly in the photosynthetic processes in which the plants absorb CO₂ from the atmosphere to produce oxygen and carbohydrates through solar radiation. We hypothesized that different climatic conditions produce significant changes regarding the carbon balance during the dry and rainy seasons.

2. Experimental

2.1 Sampling site description

This study was conducted in the REPSA, located southeast of Mexico City (19° 17' N, 99° 11' W). It covers an area of approximately 273 hectares and its nominal elevation is 2329 masl. The vegetation consists of xerophilous shrubs and dominant life forms are herbs and shrubs (Castillo-Argüero *et al.*, 2007; Chávez and Ceballos, 2009). According to Jáuregui (2000) the climate has dry and rainy seasons. The dry season runs from November to May and the rainy

season from June to October. The average annual precipitation is 803 mm and mean annual temperature is 15.6 °C.

Figure 1 shows monthly average temperature and precipitation for 2010, obtained from a weather station near the sampling point. The highest temperature during that year was recorded in May with an average value of 20 °C, and the lowest was 12 °C in December. The highest precipitation was 255 mm in July and the lowest values were 3 and 0 mm in November and December, respectively.

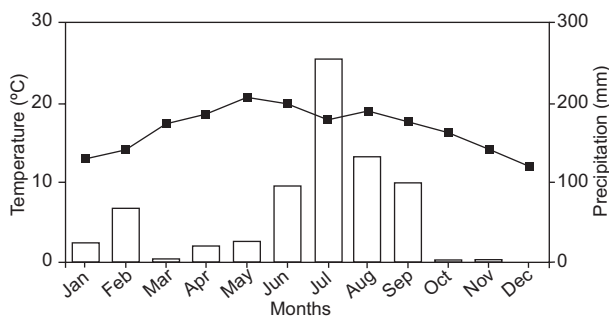


Fig. 1. Temperature and precipitation during 2010.

2.2 Sampling

The studies of CO₂ exchange were made on three sampling times: T1 (7:30-9:30 LT), T2 (11:30-13:30 LT) and T3 (15:30-17:30 LT). The sampling times were chosen because two of the selected plants have C3 metabolism and light saturation curves ranged from 500 to 1000 $\mu\text{mol m}^{-2}\text{s}^{-1}$. The experimental campaign was conducted during 2010, on February 8-12, March 8-12, April 12-16, July 5-9, August 16-20, September 6-10, October 11-15, and November 8-12.

The photosynthetic rate (PR), temperature (T), and relative humidity (RH) were measured with a LI-6400 CO₂ analyzer (LI-COR Inc., NE, USA) on leaves of each species exposed to sun. Additionally, the photosynthetic photon flux density (PPFD) was measured with an LI-190SA external sensor (LI-COR Inc., NE, USA). The experimental measurements consisted of three replicates per plant during the three sampling times.

2.3 Plants

Measurements were conducted in situ considering three native and abundant REPSA's species. *E. gibbiflora* is a perennial plant with succulent leaves and stems, belonging to the Loganiaceae family

(Carrillo-Reyes *et al.*, 2009). This plant blooms from November to February, and its leaves have a 24-30 cm long diameter forming a rosette (Pérez-Calix, 2008). *B. cordata* is an evergreen small tree, belonging to the Loganiaceae family; it blooms from July to October with oblong and pubescent leaves (5-24 cm long, 1.5-10.5 cm wide). *S. praecox* belongs to the Asteraceae family, and it has a similar lifestyle to *B. cordata* specie with oblong leaves 2-18 cm long and 2-10 cm wide, which reduces its canopy leaf area during the dry season. *E. gibbiflora* has a Crassulaceae acid metabolism known as CAM which allows the fixation of CO₂ at night, while in the light period it assimilates CO₂ into chloroplasts by the C3 cycle (Taiz and Zeigel, 2006). *S. praecox* and *B. cordata* have a Calvin-Benson cycle metabolism, allowing the fixation and assimilation of CO₂ to form organic compounds, and the photosynthesis takes place in chloroplasts (Nobel, 2009).

2.4 Population and density

In order to estimate the number of individuals from each species in the REPSA, eight quadrants of 10 by 10 m were selected. The sampling method was selective: the numbers of individuals, branches and leaves were counted in each quadrant for the three species in both climatic seasons.

In order to calculate the total CO₂ captured and emitted by the REPSA, we averaged the number of individuals for each species in eight quadrants. The results (six, seven and 79 for *B. cordata*, *S. praecox*, and *E. gibbiflora*, respectively) were then extrapolated to the REPSA. We also used the average leaf area (LA) to calculate the surface and average branches per species, in order to estimate the total contribution of REPSA. Applying a destructive method, samples and branches were taken randomly from each species in all quadrants, and then the leaf area was measured using a LI-3000 (LI-COR Inc., NE, USA).

2.5 Estimation of CO₂ (capture and emission)

The CO₂ exchange between the species and the atmosphere was estimated using average values of the photosynthetic rate, plant population and leaf area of each plant during three schedules in both seasons (dry and rainy). The estimation of CO₂ was performed with the following equation:

$$\text{CO}_2 \text{ (estimated)} = (\text{PR} \times t \times \text{LA})/\text{RA}$$

where PR represents the photosynthetic rate (kg CO_2), t the sampling time (s), LA the leaf area (m^2), and RA the REPSA area (m^2). Positive values of CO_2 indicate capture and negative values represent emissions from the plant to the environment.

2. 6 Statistical analysis

Correlation coefficient was used to test relations of PR among temperature, PPFD and relative humidity (Statistics R2015a, Matlab). Data are presented as the means of three tests and standard error.

3. Results and discussion

3.1 Photosynthetic rate, photosynthetic photon flux density, temperature and relative humidity

The maximum average temperature was 27°C in April (dry season), while the minimum was 22°C measured in September, at the end of the rainy season. Figure 2 shows the averages of PR, PPFD, T and RH for the three sampling times. We also analyzed the correlation coefficients between these variables.

The PR changed both in the dry and rainy seasons for all species (Fig. 2a, d, g). *B. cordata* had a maximum PR of $29 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in April and a minimum of $5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in October (Fig. 2a); it also showed a good correlation between PR and PPFD.

However, T and RH showed very poor correlations (Table I). *S. praecox* loses its leaves during the dry season; in April PR reached $27 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, in October it decreased to $4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, from July to October it ranged from 6.72 to $4.28 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and in April it increased to $27 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ showing a strong change from one season to another (Fig. 2d). Temperature range was 21 - 23°C in the rainy season and 28°C in the dry season (Fig. 2e), both cases showing a good correlation among PR, PPFD, and T ($r = 0.96$, Table I). *E. gibbiflora* had a totally different behavior and the correlation coefficients of PR indicated respiration instead of photosynthesis processes. PR increased from -57 to $-21 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ from February to April, but in the rainy season it was positive, ranging from 1 - $5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Also, PPFD changed from $600 \mu\text{mol m}^{-2} \text{ s}^{-1}$ during the dry season to $350 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in the rainy season (Fig. 2g). PR and PPFD had an $r = -0.78$, perhaps indicating an inverse relationship between both variables.

Analysis of normalized difference vegetation indexes (NDVI) was also performed to identify changes of greenery in both measuring seasons, using information of the MODIS from the Earth Observing

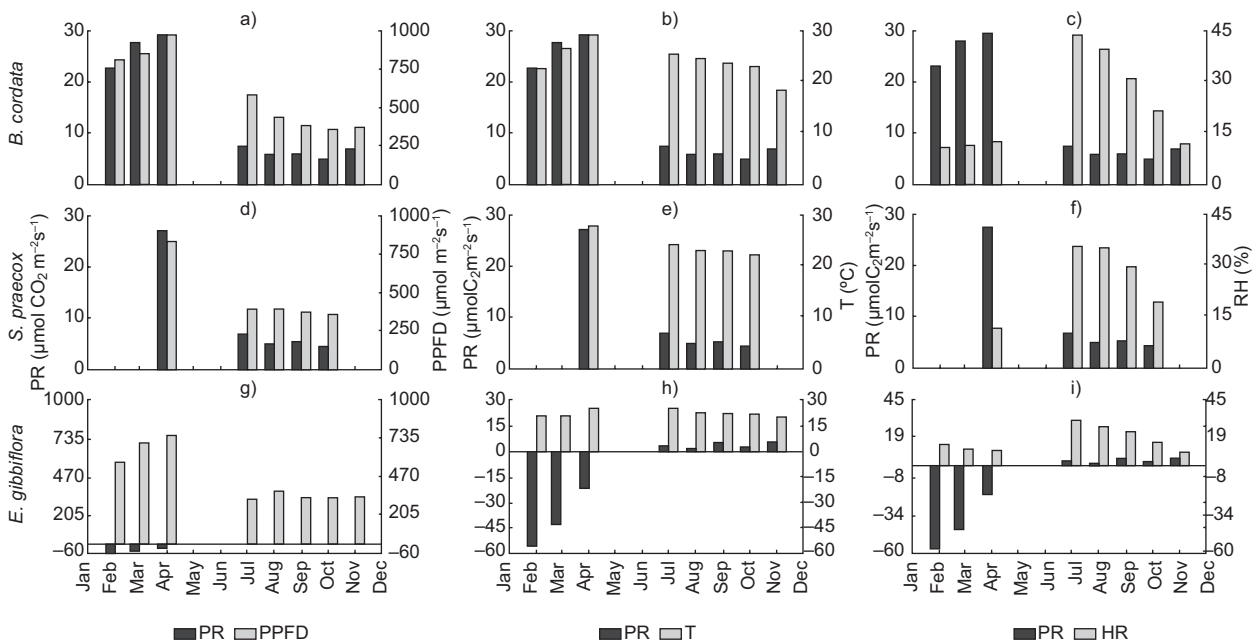


Fig. 2. Photosynthetic rate vs. photosynthetic photon flux density averages (a, d, and g); photosynthetic rate vs. temperature (b, e and h), and photosynthetic rate vs. relative humidity (c, f and i) for *B. cordata*, *S. praecox* and *E. gibbiflora*, respectively.

Table I. Cross correlation of variables for *B. cordata*, *S. praecox* and *E. gibbiflora*.

	PR (CO ₂ μmol m ⁻² s ⁻¹)	T (°C)	PPFD (μmol m ⁻² s ⁻¹)	RH (%)
<i>B. cordata</i>				
PR (μmol m ⁻² s ⁻¹)	1.00	0.58	0.97	-0.66
T (°C)		1.00	0.68	0.12
PPFD (μmol m ⁻² s ⁻¹)			1.00	-0.49
RH (%)				1.00
<i>S. praecox</i>				
PR (μmol m ⁻² s ⁻¹)	1.00	0.97	1.00	-0.74
T (°C)		1.00	0.96	-0.56
PPFD (μmol m ⁻² s ⁻¹)			1.00	-0.74
RH (%)				1.00
<i>E. gibbiflora</i>				
PR (μmol m ⁻² s ⁻¹)	1.00	0.32	-0.78	0.50
T (°C)		1.00	0.16	0.29
PPFD (μmol m ⁻² s ⁻¹)			1.00	-0.63
RH (%)				1.00

System (EOS). Figure 3 shows the results and changes on greenery along the year. July presented the highest value of the rainy season.

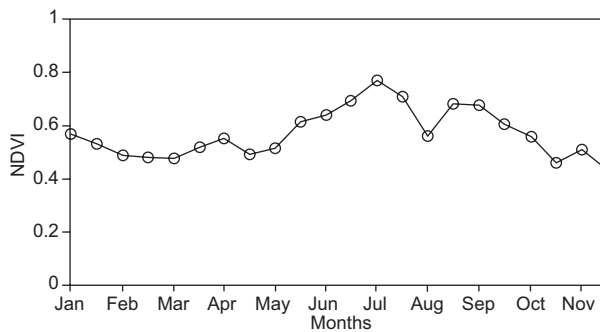


Fig. 3. Annual NDVI changes on greenery in 2010.

3.2 Estimated CO₂ (capture and emission)

Table II shows the results of CO₂ fluxes (capture and emission) estimated in the REPSA. *B. cordata* and *S. praecox* species had similar behavior in capturing CO₂ during both seasons, with 4.03 and 3.25 kg CO₂ in the three sampling times. During the rainy season there was a reduction in the capture of CO₂, decreasing to 3.25 kg for *B. cordata* and 0.63 kg for *S. praecox*. On the other hand, *E. gibbiflora* showed negative values in February, March, and April, indicating respiration processes, so the average emitted CO₂ was 11.44 kg in the dry season and the average captured CO₂ was 1.12 kg in the rainy season.

PR and PPFD for *B. cordata* and *S. praecox* showed a similar behavior on both the dry and rainy seasons. Those species had higher PR in the dry than in the rainy season. The results show the relevance of solar radiation by increasing the photosynthetic rate for this species (Larcher, 2003; Marur and Faria, 2006).

E. gibbiflora had a totally different behavior, PR showed negative values on the dry season, indicating respiration and therefore CO₂ released to the environment. The results are related to the facultative metabolism (Crassulacean acid metabolism) that captures CO₂ during the night to prevent the loss of water and also decreases its photosynthetic rate during the day. However, in the rainy season, this species showed photosynthetic activity capturing carbon dioxide probably caused by stomatal opening in short periods of the day (Geydan and Melgarejo, 2005; Andrade *et al.*, 2007).

Temperature has a direct influence on the activities of plants; it promotes physiological activities, increasing the photosynthetic rate (Lambers *et al.*, 2008), but high temperatures cause stomata closure reducing gas exchange. The environmental temperature average throughout the measuring campaign was 25 °C, thus favoring the photosynthetic activity of *B. cordata* and *S. praecox* in this microenvironment.

Photosynthesis cycles are influenced by seasonal changes, which increase in the first months of the year and decrease during fall, with the loss of leaves (Lambers *et al.*, 2008). However, environmental variables such as temperature, PPFD and

Table II. Estimation of CO₂ fluxes by *B. cordata*, *S. praecox* and *E. gibbiflora* in both seasons.

	Dry season			Rainy season	
	PR ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	Total CO ₂ (kg)		PR ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	Total CO ₂ (kg)
<i>B. cordata</i>					
Feb	22.69	4.35	Jul	7.36	1.41
Mar	27.71	5.31	Aug	5.85	1.12
Apr	29.25	5.61	Sep	5.85	1.12
Nov	6.87	0.87	Oct	4.93	0.95
<i>S. praecox</i>					
Feb			Jul	6.72	0.81
Mar			Aug	4.75	0.57
Apr	26.97	3.25	Sep	5.25	0.63
Nov			Oct	4.28	0.52
<i>E. gibbiflora</i>					
Feb	-57.05	-22.44	Jul	3.21	1.26
Mar	-43.72	-17.19	Aug	1.17	0.46
Apr	-21.16	-8.32	Sep	5.25	2.06
Nov	5.57	2.19	Oct	2.85	1.12

RH are determinant for photosynthesis responses. According to the results, the RH average was 11% during the dry season, suggesting that low RH values are appropriate for CO₂ capture by *B. cordata* and *S. praecox*. Average RH during rainy season increased to 40%, reducing plant transpiration and preventing water loss. Some studies show that in forests, clouds dipping favors photosynthesis (Letts and Mulligan, 2005; Johnson and Smith, 2008), but in these species sunny days are essential. NDVI showed that in the reserve, greenness intensity is greater than 0.4; this value is an indicator that suggests photosynthesis and secures primary productivity in this place.

The results showed a decrease of PR and PPFd during the rainy season for the species *B. cordata* and *S. praecox*. It has been suggested that clouds present in this season affect the processes of photosynthesis. It was also observed that the microenvironment and physiological variables of these species are critical in their response to photosynthesis. The contribution of the reserve according to the estimates, allows knowing the CO₂ balance of these two species during the dry and rainy seasons, which was 3.86 and 3.03 kg CO₂, respectively.

4. Conclusions

Results are a first approximation to CO₂ exchange in an urban ecosystem. This information could be integrated into ecosystem models to update and validate data. *B. cordata* and *S. praecox* have a similar

behavior in CO₂ exchange, but *E. gibbiflora* shows a totally different behavior that could overestimate the CO₂ capture in the REPSA. For a better understanding of CO₂ exchange in this reserve, we recommend that night measurements should be performed too.

Acknowledgments

We thank M. I. Saavedra for her technical assistance; also H. Padilla, J. García, E. Montes, A. Ysunza, J. Rosas, R. López, E. Galindo, and T. Castillo for their help during the measuring campaign.

References

- Andrade J. L., E. de la Barrera, C. Reyes-García C, M. F. Ricalde M.F, G.Vargas-Soto and J. C. Cervera, 2007. El metabolismo ácido de las crasuláceas: diversidad, fisiología ambiental y productividad. *Bol. Soc. Bot. Méx.* 81, 37-50.
- Carrillo-Reyes P., V. Sosa and M. E. Mort, 2009. Molecular phylogeny of the Acre clade (Crassulaceae): Dealing with the lack of definitions for *Echeveria* and *Sedum*. *Mol. Phylogenet. Evol.* 53, 267-276, doi: 10.1016/j.ympev.2009.05.022.
- Castillo-Argüero S., Y. Martínez Orea, M. A. Romero Romero, P. Guadarrama Chávez, O. Núñez Castillo, I. Sánchez Guillén and J. A. Meave, 2007. *La Reserva Ecológica del Pedregal de San Ángel, aspectos florísticos y ecológicos*. Secretaría Ejecutiva de la Reserva Ecológica del Pedregal de San Ángel de Ciudad Universitaria, México, 11-15.

- Chávez C. and G. Ceballos, 2009. Implications for conservation of the species diversity and population dynamics of small mammals in an isolated reserve in Mexico City. *Nat. Area. J.* 29, 27-41, doi: <http://dx.doi.org/10.3375/043.029.0104>.
- FAO, 2010. *Evaluación de los recursos forestales mundiales 2010*. Organización de las Naciones Unidas para la Agricultura y la Alimentación, Roma, 11-45, ISBN 97892-5-306654-4.
- Geydan T. D. and L. M. Melgarejo, 2005. Metabolismo ácido de las crasuláceas. *Acta Biológica Colombiana* 10, 3-15.
- Harnos N., Z. Nagy, J. Balogh, Z. Tuba, 2006. Modeling net photosynthetic rate of temperate dry grassland species and winter wheat at elevated air CO₂ concentration. *Appl. Ecol. Env. Res.* 4, 47-53.
- IPCC, 2007. Summary for policymakers. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, 1-18.
- INE, 2010. Inventario Nacional de Emisiones de Gases Efecto Invernadero (IV). Instituto Nacional de Ecología y Cambio Climático, México, 384 pp.
- Jáuregui O. E., 2000. El clima de la Ciudad de México, Instituto de Geografía, Universidad Nacional Autónoma de México, México, 139 pp.
- Johnson D. M. and W. K. Smith, 2008. Cloud immersion alters microclimate, photosynthesis and water relations in *Rhododendrom catawbiense* and *Abies fraseri* seedlings in the southern Appalachian Mountains, USA. *J. Exp. Bot.* 47, 639-645.
- Kim S. H. and J. H. Lieth, 2003. A coupled model of photosynthesis, stomatal conductance and transpiration for a rose leaf (*Rosa hybrida* L). *Ann. Bot.* 91, 771-781, doi:10.1093/aob/mcg080.
- Kitao M., T. T. Lei, T. Koike, M. Kayama, H. Tobita and Y. Maruyama, 2007. Interaction of drought and elevated CO₂ concentration on photosynthetic down regulation and susceptibility to photo inhibition in Japanese white birch seedlings grown with limited N availability. *Tree Physiol.* 27, 727-735.
- Kordowski K. and W. Kuttler, 2010. Carbon dioxide fluxes over an urban park area. *Atmos. Environ.* 44, 2722-2730, doi:10.1016/j.atmosenv.2010.04.039.
- Lambers H., F. S. Chapin and T. L. Pons, 2008. *Plant physiological ecology*. Springer, New York, 605 pp.
- Larcher W., 2003. *Physiological plant ecology. Ecophysiology and stress physiology of functional groups*. Springer, Berlin, 514 pp.
- Letts M. G. and M. Mulligan, 2005. The impact of light quality and leaf wetness on photosynthesis in the north-west Andean tropical, montane cloud forest. *J. Trop. Ecol.* 21, 549-557, doi:10.1017/S0266467405002488.
- Long S. P. and C. J. Bernacchi, 2003. Gas exchange measurements, what can they tell us about the underlying limitations to photosynthesis? Procedures and sources of error. *J. Exp. Bot.* 54, 2393-2401, doi:0.1093/jxb/erg262.
- Marur C. J. and R. T. Faria, 2006. Photosynthesis of individual leaves in a coffee plant. *Acta Sci.-Agron.* 28, 331-335.
- Myers D. A., R. B. Thomas and E. H. de Lucia, 1999. Photosynthetic responses of loblolly pine (*Pinus taeda*) needles to experimental reduction in sink demand. *Tree Physiol.* 19, 235-242.
- NOAA 2014. Annual Data Atmospheric CO₂ Concentration. Mauna Loa CO₂ Data IOP Publishing: PhysicsWeb. Available at: <https://www.climate.gov/news-features/understanding-climate/2014-state-climate-carbon-dioxide>.
- Nobel Park S., 2009. *Physicochemical and environmental plant physiology*. Academic Press, California, 567 pp.
- Okimoto Y., A. Nose, Y. Katsuta, Y. Tateda, S. Agarie and K. Ikeda, 2007. Gas exchange analysis for estimating net CO₂ fixation capacity of mangrove (*Rhizophora stylosa*) forest in the mouth of river Fukido, Ishigaki Island, Japan. *Plant Prod. Sci.* 10, 303-313, doi:10.1626/pps.10.303.
- Pérez-Calix E., 2008. Crassulaceae. *Flora del Bajío y de Regiones Adyacentes* 156, 1-141.
- Rzedowski J., 1954. Vegetación del Pedregal de San Ángel (Distrito Federal, México). *Anales de la Escuela Nacional Ciencias Biológicas* 8, 59-129.
- Sharkey T. D., C. J. Bernacchi, G. D. Farquhar and E. L. Singsaas, 2007. Fitting photosynthetic carbon dioxide response curves for C3 leaves. *Plant Cell Environ* 30, 1035-1040, doi:10.1111/j.1365-3040.2007.01710.x.
- Schultz R. H., 2003. Extension of a Farquhar model for limitations of leaf photosynthesis induced by light environment, phenology and leaf age in grapevines (*Vitis vinifera* L. cvv. White Riesling and Zinfandel). *Functional Plant Biology* 30, 673-687, doi:10.1071/FP02146.
- Taiz L. and E. Zeigel, 2006. *Plant physiology*. Sinauer Associates, Sunderland, 623 pp.

- Velasco E., M. Roth., S. H. Tan, M. Quak, S. D. A. Nabarro and L. Norford, 2013. The role of vegetation in the CO₂ flux from a tropical urban neighborhood. *Atmos. Chem. Phys.* 13, 7267-7310, doi:10.5194/acp-13-10185-2013.
- Xu L. and D. D. Baldocchi, 2003. Seasonal trends in photosynthetic parameters and stomatal conductance of blue oak (*Quercus douglasii*) under prolonged summer drought and high temperature. *Tree Physiol.* 23, 865-877.
- Yang J., J. McBride, J. Zhou and Z. Sun, 2005. The urban forest in Beijing and its role in air pollution reduction. *Urban For. Urban Gree.* 3, 65-78, doi: doi:10.1016/j.ufug.2004.09.001.
- Zhao M., F. A. Heinsch, R. R. Nemani and S. W. Running, 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sens. Environ.* 95, 164-176, doi:10.1016/j.rse.2004.12.011.