Diurnal CO2 Fluxes of Different Seyhan Watershed Ecosystems

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1.Introduction

Carbon (C) cycle couples all the abiotic and biotic components of ecosystems to one another on a variety of temporal and spatial scales. Increased rates and magnitudes of fossil fuel consumption, and land-use and land-cover changes are the main anthropogenic disturbances of biogeochemical C cycle at the local scale that trigger climate change at the global scale.[1] Since the coldest point of the last great ice age, which ended about 10,000 years ago, the mean temperature of the Earth's surface has increased by only 5°C.[2] Over the past century, the global mean air temperature has increased by about 0.5°C (+0.2) despite observed decreases in lower stratospheric ozone and increases in sulphate particles that both produce cooling effects (a negative radiative forcing).[3] During the period 1951 to 1990, the rise of the minimum nighttime temperature occurred at a rate three times that of the maximum daytime temperature for over 50% of landmass in the Northern Hemisphere and 10% of landmass in the Southern Hemisphere.[4] General circulation models (GCMs) suggest a global mean temperature increase ranging from 1°C to 4.5°C with a doubled atmospheric carbon dioxide (CO_2) concentration (700 ppmv) by the year 2100 if mitigative measures to reduce the present rate of production of GHGs are not taken.[5,6]

The key regulators of productivity and respiration of Mediterranean ecosystems are interactively climatic constraints of the Mediterranean climate such as concentration of rainfall in winter, a distinct summer drought, warm-to-hot summers, and cool-to-cold winters[7]; more frequent and longer droughts as projected by global climate change; and a long history of human-induced disturbances.[8,9] As a consequence, establishing preventive and mitigative measures at the local scales towards stabilization of atmospheric CO_2 concentration depends on a better understanding and quantification of ecosystem C dynamics temporally and spatially.[10,11] Objective of the study was to quantify diurnal patterns of variations in CO_2 fluxes in different Mediterranean ecosystems of Seyhan watershed (Adana, Turkey).

2.Materials and methods

Study region

Study sites (37°04′-36°46′N, 35°20′-35°25′E) are located in Seyhan watershed of *ca.* 21,000 km^2 in a southern Mediterranean region of Turkey at an altitude 6 to 150 m above sea level. A typical Mediterranean climate prevails in the study region with the long term mean annual temperature, precipitation, potential evapotranspiration, and incident photosynthetically active radiation (PAR) of 18.7°C, 647 mm, 1320 mm, and 284 MJ m^{-2}, respectively. Minimum and maximum air temperatures are -8.1 in January and 45.6 in August, respectively. About 87% of precipitation falls from November to May. Maximum incident PAR occurs in August (415.6 MJ m^{-2} month^{-1}) and the minimum in December (141.4 MJ m^{-2} month^{-1}). Dominant soils of the study sites are Typic Xerofluvent in the citrus, cotton and soybean sites, Typic Chromoxerert in the vineyard site, Aquic Xerofluvent in the corn site, and Typic Xerorthent in the forest site.[12] According to the bioclimatic scheme by Holdridge (1947), the dominant vegetation cover is subtropical dry forest.[13] In general, dominant forest tree species include *Pinus brutia*, *Pinus pinea*, *Quercus ilex*, *Pinus nigra*, *Cedrus libani*, *Juniperus excelsa*, and *Abies cilicica*, while dominant woody understory species include *Phillyrea latifolia*, *Pistacia terebinthus*, *Quercus coccifera*, *Styrax officinalis*, *Arbutus andrachne*, *Cistus creticus*, and *Mrytus* *communis*.[14]

3.Sampling and analyses of data

Continuous sampling was carried out on a diurnal basis in six typical Mediterranean ecosystems of Seyhan watershed along south-to-north and east-to-west transects on June 16-25 of 2003: (1) three co-occurring evergreen forest species: one conifer tree (*Pinus pinea* L.) and two sclerophyllous shrubs (*Pistacia terebinthus* L. subsp. *palaestina* (Boiss.) Engler, and *Phillyrea latifolia* L.), (2) citrus (*Citrus limon* L.), (3) corn (*Zea mays* L.), (4) cotton (*Gossypium hirsutum* L.), (5) soybean (*Glycine max* L.), and (6) vineyard (*Vitis vinifera* L.). Continuous time series data were collected by an automatic 4-channel open type monitoring system (PM-48M Photosynthesis Monitor 1.0, PhyTech, Israel) for net CO_2 assimilation (P_N, µmol m^{-2} sec^{-1}), soil respiration (R_h, µmol m^{-2} sec^{-1}), atmospheric CO_2 concentration (ppm), air temperature (°C), relative humidity (RH, %), photosynthetically active radiation (PAR, µmol m^{-2} sec^{-1}), and water vapour pressure deficit (VPD, kPa) at 30 min intervals for *ca.* 39 h (17:30-7:30) for forest, 24 h (11:00-11:00) for citrus, 21 h (13:00-11:00) for corn, 40 h (16:00-8:00) for cotton, 23 h (14:30-13:30) for soybean, and 12 h (18:00-1:00 and 12:00-17:30) for vineyard. Soil samples taken at each of the sites to depth of 0-30 cm in four replicates were analysed for field capacity, wilting point, soil texture, bulk density, soil organic carbon and nitrogen, $CaCO_3$, salt content, and pH (Table 1).

In terms of gas exchange, P_N can be defined as follows:

$$P_N = P_G - R_a \qquad (1)$$

where P_G (gross primary productivity) is the rate of C fixed from the atmosphere by photosynthesis, and R_a is the rate of C release to the atmosphere by autotrophic respiration. The net ecosystem exchange of CO_2 between the atmosphere and an ecosystem can be quantified as follows:

$$NEP = P_N - R_h \qquad (2)$$

where NEP is net ecosystem productivity, R_h is the rate of C release from the soil to the atmosphere by respiration of microorganisms and roots. We adopted the sign convention of net ecosystem sequestration (NES) of CO_2 as positive and net ecosystem emission (NEE) of CO_2 to the atmosphere as negative throughout the paper.

Statistical analyses of data were carried out using Minitab 13.32 (Minitab, Inc., U.S.A.). Correlation matrix was used to explore association of all the variables for each of the study sites. Fisher's LSD multiple comparison test was used to test for significant differences in response means among the different ecosystems following one-way analysis of variance (ANOVA). Multiple linear regression (MLR) was performed to model diurnal P_N and R_h rates as a function of two or more explanatory variables for each of the ecosystems.

4.Results and discussion

Microclimatic conditions on the dates of CO_2 flux measurements in the six ecosystems varied within the typical range for summer months in the southern Mediterranean Turkey. Daily minimum and maximum values measured were 69-1943 µmol m^{-2} s^{-1} for PAR, 21.1-41.7°C for air temperature, 0.03-6.1 kPa for VPD, 18.3-98.8% for relative humidity, and 273-483 ppm for atmospheric CO_2 concentration. The matrix of correlation coefficients showed that there was, in general, a consistent diurnal pattern of association among the variables measured for all the six ecosystems. Net CO_2 uptake by the plant, air temperature, VPD, and PAR were positively correlated ($p<0.001$). As expected, VPD and RH were negatively correlated ($p<0.001$).

There appeared to be a negative correlation between R_h and air temperature, significant only for the citrus, corn and soybean sites ($p<0.001$). Except for the forest and vineyard sites, there was a negative relationship between R_h and P_N rates. Increased air temperature led to enhanced atmospheric CO_2 uptake by photosynthesis and depressed CO_2 loss by decomposition and mineralization of soil organic matter ($p<0.001$). Thus, NEP and NES increased, and atmospheric CO_2 concentration decreased in response to increased air temperature. In other words, NEE increased as net plant uptake of CO_2 from the atmosphere decreased, and soil respiratory loss of CO_2 to the atmosphere increased. This revealed that R_h rates were more sensitive than P_N rates to high temperatures, VPD, and top-soil water deficit. This finding is consistent with the study carried out by Reichstein *et al.* (2002) in Mediterranean summer months.[15,16] This suggests that as air temperature and soil dryness increase in response to global warming alone, water relations are more likely to control R_h and P_N (particularly for C_3 species) rates and their diurnal variability in Mediterranean ecosystems.[17,18]

To test whether P_N, R_h, NEE, and LUE varied spatially across the range of the sites, LSD test following one-way ANOVA was performed. Mean values of P_N rates ranged from 0.2 μmol CO_2 m^{-2} sec^{-1} in the forest site to 3.9 μmol CO_2 m^{-2} sec^{-1} in the soybean site (Table 2). Mean P_N rates of the forest, citrus and vineyard ecosystems were significantly lower than those of the corn, cotton and soybean ecosystems ($p<0.001$) (Table 2). This revealed that the slow-growing tree and shrub species had lower P_N rates that did the fast-growing crops. Mean rates of soil respiratory loss of CO_2 were greatest (-26.8 μmol CO_2 m^{-2} sec^{-1}) in the corn site and smallest (-0.9 μmol CO_2 m^{-2} sec^{-1}) in the vineyard site. Mean R_h rates varied significantly among the sites, except for the citrus and cotton sites ($p<0.001$) (Table 2).

Mean rates of NEE ranged from -23.9 μmol CO_2 m^{-2} sec^{-1} in the corn site to -0.6 μmol CO_2 m^{-2} sec^{-1} in the vineyard site. Net ecosystem emission of CO_2 to the atmosphere differed significantly among the sites (except between citrus and cotton, and soybean and vineyard) due to the strong role of R_h in net ecosystem CO_2 exchange ($p<0.001$). On average, all the six ecosystems were responsible for a net release of CO_2 to the atmosphere, due to R_h effluxes exceeding P_N rates.

The ambient CO_2 levels generally increased from sunset and decreased gradually after sunrise, ranging from 308 to 343 ppm for forest, 309 to 380 ppm for citrus, 303 to 483 ppm for corn, 291 to 425 ppm for cotton, 304 to 427 ppm for soybean, and 308 to 460 ppm for vineyard. Rates of P_N and R_h (μmol CO_2 m^{-2} sec^{-1}) that accounted for diurnal fluctuations of the atmospheric CO_2 concentration (ppm) ranged from 25% for corn to 87% for citrus, and their MLR models are as follows:

$$\text{atmCO}_{2\text{citrus}} = 311 - 2.9\,P_N + 2.9\,R_h \qquad (3)$$
$(n = 49, r^2 = 87\%, p<0.001)$

$$\text{atmCO}_{2\text{soybean}} = 303 - 2.1\,P_N + 8.4\,R_h \qquad (4)$$
$(n = 46, r^2 = 63\%, p<0.001)$

$$\text{atmCO}_{2\text{cotton}} = 274 - 6.2\,P_N + 10.3\,R_h \qquad (5)$$
$(n = 30, r^2 = 59\%, p<0.001)$

$$\text{atmCO}_{2\text{forest}} = 321 - 7.4\,P_N + 0.5\,R_h \qquad (6)$$
$(n = 78, r^2 = 50\%, p<0.001)$

$$\text{atmCO}_{2\text{vineyard}} = 336 - 19.9\,P_N + 6.9\,R_h \qquad (7)$$
$(n = 25, r^2 = 29\%, p<0.05)$

$$\text{atmCO}_{2\text{corn}} = 318 - 3.1\,P_N + 2.1\,R_h \qquad (8)$$
$(n = 40, r^2 = 25\%, p<0.01)$

Photosynthesis and soil respiration change in response to diurnal spatial and temporal variations of environmental factors, in which solar radiation, temperature, and evaporative demand of air are the main driving factors. Air temperature increased with solar radiation after sunrise until afternoon and decreased when solar radiation decreased to a certain extent. Solar radiation peaked at noon, whereas the corresponding peaks of air temperature and VPD lagged behind by about 2 h.

Maximum values of P_N rates and their corresponding local times were 2.3 μmol CO_2 m^{-2} sec^{-1} at 08:30 for *P. pinea*, 2.7 μmol CO_2 m^{-2} sec^{-1} at 12:00 for vineyard (no data collected between 1:00 and 12:00), 2.8 μmol CO_2 m^{-2} sec^{-1} at 7:30 for *P. latifolia*, 3.4 μmol CO_2 m^{-2} sec^{-1} at 12:30 for *P. terebinthus*, 4.5 μmol CO_2 m^{-2} sec^{-1} at 8:00 for citrus, 13.7 μmol CO_2 m^{-2} sec^{-1} at 9:00 for soybean, 14.7 μmol CO_2 m^{-2} sec^{-1} at 9:30 for cotton, and 20.3 μmol CO_2 m^{-2} sec^{-1} at 13:00 for corn (Fig. 1). Except for *P. terebinthus* and corn, P_N rates of all the species peaked in the morning (7:30-9:30). Mean P_N rates of *P. latifolia*, *P. pinea*, cotton, soybean and citrus were 21%, 68%, 2%, 22% and 19% higher in the morning (7:30-11:30) than in the midday (12:00-16:00), respectively. Differences in the mean morning and midday P_N rates of *P. pinea*, soybean and citrus were significant ($p<0.05$). This revealed that P_N rates were depressed when air temperature and VPD reached their peak at about 14:00. High midday temperature and VPD resulted in a midday depression of photosynthesis caused by stomatal closure.[19,20,21] Both *P. terebinthus* and corn (a C_4 species) had 7% and 45% lower P_N rates in the morning than in the afternoon, respectively ($p>0.05$). The ratio of carbon gain to water loss in Mediterranean environments may be larger in the C_4 plants than in the C_3 plants, thus suggesting C_3 species may be more sensitive than C_4 species to global warming.[22,23] The trade-offs between CO_2 sequestration by NEP and water loss by evapotranspiration play an important role in Mediterranean ecosystems.[23,24]

Peaks of R_h rates and their corresponding local times were -3.5 μmol CO_2 m^{-2} sec^{-1} at 22:00 for vineyard, -9.2 μmol CO_2 m^{-2} sec^{-1} at 02:30 for soybean, -10.5 μmol CO_2 m^{-2} sec^{-1} at 01:30 for cotton, -18.5 μmol CO_2 m^{-2} sec^{-1} at 02:30 for citrus, -22.1 μmol CO_2 m^{-2} sec^{-1} at 19:30 for forest, and -37.2 μmol CO_2 m^{-2} sec^{-1} at 01:00 for corn. Soil respiration rates in the sites were higher during the night than during the day ($p<0.05$). Increasing temperature and drying soil caused R_h rates to decrease rather than increase in the six Mediterranean ecosystems, which highlights the re-examination of assumptions made in current climate models such as biological Q_{10}. Seasonal variation in R_h can be attributable to temperature, vegetation type, and quantity and quality of detritus supplied to the soil.[25,26] However, the influence of soil dryness on diurnal R_h rates appeared to be stronger than that of temperature, vegetation type, and quality and quantity of litterfalls.

Net ecosystem emission rates of CO_2 were greater during the night and afternoon than during the day and morning in the sites. Maximum NEE values were -38.4 μmol CO_2 m^{-2} sec^{-1} at 1:00 for corn, -22.2 μmol CO_2 m^{-2} sec^{-1} at 19:30 for forest, -18.9 μmol CO_2 m^{-2} sec^{-1} at 2:30 for citrus, -12.8 μmol CO_2 m^{-2} sec^{-1} at 1:30 for cotton, -10.6 μmol CO_2 m^{-2} sec^{-1} at 2:30 for soybean, and -4.5 μmol CO_2 m^{-2} sec^{-1} at 22:00 for vineyard. The forest site was a net source of CO_2 to the atmosphere during the measurement, with a minimum NEE value of -9.6 μmol CO_2 m^{-2} sec^{-1} at 13:00. However, the other sites showed daytime NES rates of varying durations and magnitudes. The citrus ecosystem sequestered CO_2 between 11:00 and 16:00 at a maximum NES rate of 1.9 μmol CO_2 m^{-2} sec^{-1} at 13:00, while the soybean ecosystem was a net sink of CO_2 between 7:00 and 18:00, with a maximum NES rate of 10.2 μmol CO_2 m^{-2} sec^{-1} at 10:30. The corn, cotton and vineyard sites had maximum NES rates of 4.5, 2.5 and 1.4 μmol CO_2 m^{-2} sec^{-1} at 13:30, 8:00 and 14:00, respectively. Maximum NEE and NES rates, in general, coincided with maximum and minimum R_h rates in the sites, respectively.

5.Conclusions

The rates of plant CO_2 assimilation, soil CO_2 sequestration, and their response to changing environmental conditions are of primary importance given the projections of global climate change. High levels of temperature, solar radiation and VPD along with low water availability in the soil that prevail during summer months in a Mediterranean climate induce further stresses on Mediterranean ecosystems.[27,28] The relative importance of variables such as temperature, VPD, and soil moisture in P_N and R_h rates varies by climate, ecosystems, and temporal scales.[29,30] The study revealed that the temperature sensitivity of R_h rates in the sites depended on soil moisture and increased with high soil moisture during the night and decreased with low soil moisture during the day. Similarly, P_N rates were lower at noon when PAR peaked than in the morning due to high VPD and/or soil water deficit. The rise of the minimum nighttime temperature as a consequence of global climate change may further increase R_h rates, thus contributing to net sources of CO_2 to the atmosphere within Mediterranean ecosystems. To better understand and predict short- and long-term responses to global climate change across different ecosystems, we need further investigations on temporal and spatial variability in R_h and P_N rates, and ecosystem CO_2 dynamics.

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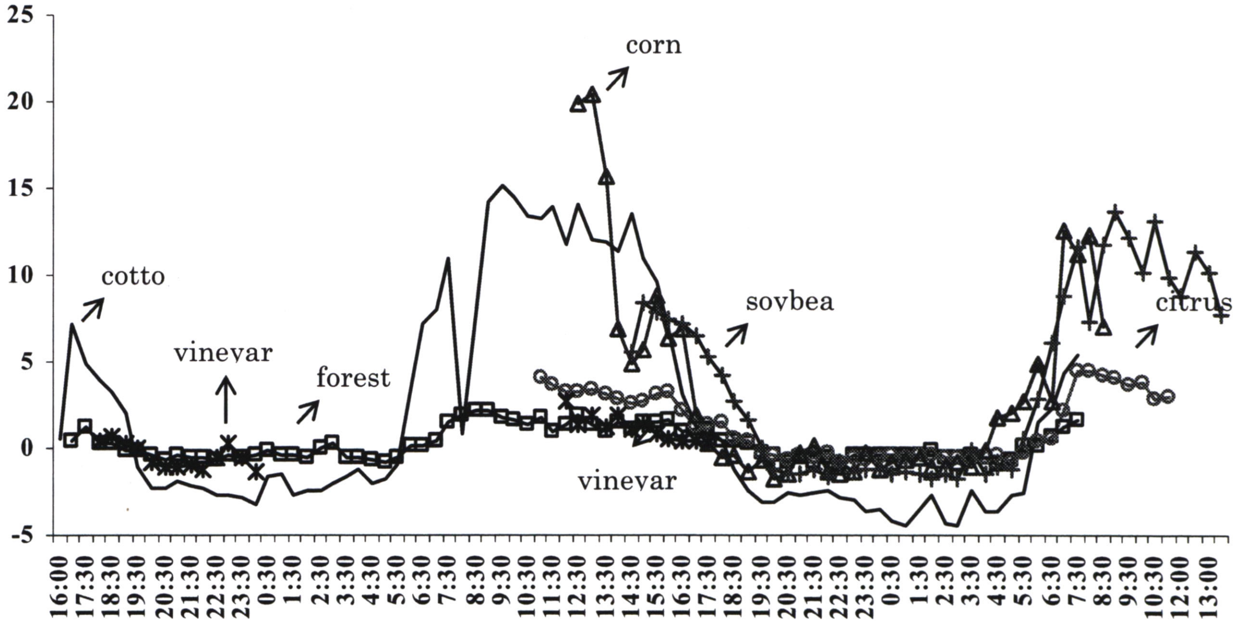

Fig. 1 Diurnal variations in net photosynthetic rates by Mediterranean forest (Pistacia terebinthus L. subsp. palaestina (Boiss.) Engler, Phillyrea latifolia L., and Pinus pinea), citrus, corn, cotton, soybean and vineyard ecosystems in June.

Table 1 Some physical, chemical and biological properties of soil samples (0-30 cm) taken along south-to-north and west-to-east transects of Seyhan watershed (n = 4)[a]

Ecosystem type	Soil texture (clay-silt-sand %)	Field capacity (% volume)	Wilting point (% volume)	BD (g cm^{-3})	Salt (%)	$CaCO_3$ (%)	pH	SOC (%)	SON (%)	C/N
Forest	clay 57-39-4	34.70 (2.6)a	25.93 (1.3)a	1.26 (0.1)a	0.06 (0.01) a	29.79 (2.8)a	7.7 (0.1) a	0.52 (0.2) a	0.05 (0.02)a	10
Citrus	silty clay 44-40-16	32.76 (2.5)b	25.32 (3.6)a	1.42 (0.2)b	0.06 (0.01) ab	24.42 (0.6)b	7.7 (0.1) a	0.76 (0.1) b	0.11 (0.01)b	7
Corn	clay loam 33-46-21	31.43 (1.8)cb	23.63 (2.1)ba	1.53 (0.1)c	0.06 (0.01) b	17.87 (1.4)c	7.7 (0.1) a	0.80 (0.2) cb	0.10 (0.02)c	8
Cotton	clay loam 32-34-34	27.07 (3.1)d	17.29 (2.2)c	1.33 (0.1)d	0.05 (0.01) cd	32.68 (1.4)d	7.7 (0.1) a	0.43 (0.04)d	0.09 (0.01)d	5
Soybean	clay loam 39-38-23	34.89 (2.5)a	25.89 (3.1)ae	1.47 (0.1)eb c	0.05 (0.01) d	19.52 (0.9)ef	7.8 (0.1) b	0.33 (0.1) e	0.08 (0.02)e	4
Vineyard	clay 71-22-7	41.67 (5.2)e	31.64 (5.1)df	1.26 (0.2)a	0.08 (0.01)	18.98 (5.1)f	7.9 (0.1)	0.57 (0.1)	0.08 (0.01)f	7

Table 2 Mean values and standard errors of environmental variables for the different Mediterranean ecosystems [a]

Sites	n	P_N (μmol m^{-2} sec^{-1})	n	R_h (μmol m^{-2} sec^{-1})	NEE (μmol m^{-2} sec^{-1})	PAR (μmol m^{-2} sec^{-1})	Atm. CO_2 (ppm)	T (°C)	RH (%)	VPD (kPa)
Forest	234	0.24 (0.1)a	78	-14.92 (0.3)a	-14.7 (0.3)a	318.7 (55.4)a	326 (1.1)a	26.9 (0.4)a	75.8 (1.8)a	1.0 (0.1)a
PT	78	028 (02)								
PL	78	0.44 (0.1)								
PP	78	0.01 (0.1)								
Citrus	147	1.35 (0.3)a	49	-8.86 (0.8)b	-7.5 (1.0)bd	449.8 (84.3)ab	332 (3.2)ac	27.4 (0.5)ab	71.1 (1.8)a	1.2 (0.1)ae
Corn	120	2.91 (0.9)bc	40	-26.76 (0.9)c	-23.9 (1.5)c	511.0 (99.5)abc	364 (8.0)b	26.2 (0.6)a	77.1 (2.8)a	0.9 (0.1)a
Cotton	237	2.88 (0.6)c	30	-7.75 (0.3)db	-6.9 (0.6)d	420.9 (67.5)ab	343 (3.5)c	28.3 (0.7)ad	71.4 (2.5)a	1.6 (0.2)be
Soybean	138	3.86 (0.8)dc	46	-5.62 (0.3)e	-1.8 (1.0)ef	560.8 (96.4)bd	342 (5.0)dc	29.4 (0.9)bde	69.6 (3.2)a	1.7 (0.2)ce
Vineyard	75	0.31 (0.2)a	25	-0.87 (0.2)f	-0.6 (0.3)f	765.0 (158)cd	336 (8.5)ac	31.8 (1.4)ce	52.6 (6.8)b	3.0 (0.5)d

[a] Means with different letters for each of the variables denote significant differences at $p<0.001$ as determined by the LSD test. Values in parentheses refer to standard errors. PT: *Pistacia terebinthus* L. subsp. *palaestina* (Boiss.) Engler, PL: *Phillyrea latifolia* L., PP: *Pinus pinea*, P_N: net photosynthesis, R_h: soil respiration, NEE: net ecosystem emission of CO_2, T: air temperature, PAR: photosynthetically active radiation, VPD: vapour pressure deficit, and RH: relative humidity. n = 79 in the soybean site for all environmental variables except for P_N and R_h. Net ecosystem CO_2 uptake and CO_2 loss were designated as positive and negative signs, respectively.