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ANNUAL AND DIURNAL CYCLES OF THE INVERSE RELATION BETWEEN PLANT TRANSPIRATION AND CARBON SEQUESTRATION

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ABSTRACT

Understanding biogeochemical cycles and especially carbon budgets is clue to validate global change models in the present and near future. As a consequence, sinks and sources of carbon in the world are being studied. One of those sinks is the non-well known behavior of the planet vegetation which involves the processes of photosynthesis and respiration. Carbon sequestration rates are highly related to the transpiration through a molecular diffusion process occurring at the stomatal level which can be recorded by an eddy covariance micrometeorological station. This paper explores annual and diurnal cycles of latent heat (LE) and CO_2 net (FC) fluxes over 6 different ecosystems. Based on the physics of the transpiration process, different time-scale analysis are performed, finding a near-linear relation between LE and CO_2 net fluxes, which is stronger at the more vegetated areas. The North American monsoon season increases carbon up taking and LE-CO_2 flux relation preserves at different time scales analysis (hours to days to months).

KEY WORDS: carbon sequestration; evapotranspiration; net exchange of $CO_{2;}$ eddy covariance; latent heat flux; diurnal cycle; annual cycle; Southwestern North America.

RESUMEN

El conocimiento de los ciclos biogeoquímicos y, en especial, de los balances de carbono es clave para la validación de los modelos de cambio global para el presente y el futuro cercano. Como consecuencia, en el mundo se estudian las fuentes y los sumideros de carbono. Uno de esos sumideros es la vegetación del planeta, que involucra los procesos de respiración y fotosíntesis y cuyo comportamiento se empieza a estudiar. Las tasas de captura del carbono están muy ligadas a la transpiración mediante un proceso de difusión molecular en los estomas, que puede registrarse por un sistema micrometeorológico de eddy covarianza.

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Este artículo explora los ciclos anuales y diurnos de los flujos netos de CO_2 y calor latente de seis ecosistemas diferentes. Se desarrollan diversos análisis de escala temporal, basados en la física de la transpiración, y se halla una relación cuasilineal entre los flujos netos de calor latente y CO_2, más fuerte en las áreas con mayor cobertura vegetal. La temporada del monzón norteamericano incrementa la captura de carbono y la relación entre la evapotranspiración y el intercambio de gas carbónico se mantiene en las diferentes escalas temporales analizadas (horas, días, meses).

PALABRAS CLAVE: fijación de carbono; evapotranspiración; intercambio neto de CO_2; eddy covarianza; flujo de calor latente; ciclo anual; ciclo diurno; Suroeste de Norteamérica.

1. INTRODUCTION

Vegetation processes respond widely different according to seasonal, age, soil moisture and particular ambient settings. Such response of vegetation to the surrounding environment is a key global change issue that scientists are investigating by using measurements and models at short and long term scales (Fang, Xue and Tang, 2007; Byrne, Kiely and Leahy, 2007; Byrne *et al.*, 2007; Litynski *et al.*, 2006; Chen *et al.*, 2007; Lal, 2005; Brack, 2002; Law *et al.*, 2002 and Zhan and Kustas, 2001). Earlier work suggested that annual productivity increased with mean annual temperature and precipitation (Lieth, 1972a,b; O'Neill and DeAngelis, 1981). Concurrently, leaf-level studies suggested a mechanism for optimal stomatal variation that regulates the relationship between water loss through assimilation in response to the environment (Cowan, 1977). The net ecosystem exchange (NEE) of CO_2 between the biosphere and atmosphere is the balance between fluxes associated with photosynthetic assimilation by the foliage (gross ecosystem production) and respiratory effluxes from autotrophs (R_a) and heterotrophs (R_h). Differences in annual NEE between locations might be attributable to disturbance history, climate, nutrition, biome type and physiological differences associated with age (Law *et al.*, 2002; Schulze *et al.*, 1999). Environmental conditions may influence photosynthetic uptake and autotrophic and heterotrophic respiration differently. Research in European forests showed that there was no correlation between GEP and latitude, but annual ecosystem respiration increased with latitude, in spite of decrease in mean annual temperature.

Transpiration is the evaporation of excess of water from aerial parts of plants especially leaves but also stems, flowers, and fruits. Transpiration is a side effect of the plant needing to open its stomata in order to obtain carbon dioxide gas from the air for photosynthesis. Transpiration also cools plants and enables mass flow of mineral nutrients from roots to shoots. Mass flow is caused by the decrease in hydrostatic (water) pressure in the upper parts of the plants due to the diffusion of water out of stomata into the atmosphere. The rate of transpiration is directly related to whether the stomata are open or closed. The amount of water lost by a plant depends on its size, along with the surrounding light intensity, temperature, humidity, wind speed, and soil water supply. The reason that an increase in temperature will cause an increase in transpiration rate is because an increase in temperature will cause more water to evaporate from the cell walls. This will increase the water potential gradient between the leaf interior and the outside air causing water to leave the leaf more quickly, thereby increasing the rate of transpiration. The transpiration ratio is the ratio of the mass of water transpired to the mass of dry matter produced; the transpiration ratio of crops tends to fall between 200 and 1000, for instance, crop plants transpire 200 to 1000 kg of water for every kg of dry matter produced (Martin, Leonard and Stamp, 1976).

The carbon budget of a tree (or any plant) can be expressed much like a balance in terms of the uptake of CO_2 a plant can do:

Income = carbohydrates manufactured in photosynthesis

Expenditures = carbohydrates used in growth and maintenance (construction and maintenance respiration)

Balance = carbohydrates stored (so-called non-structural carbohydrates and other storage compounds)

The carbon balance of a tree is very much related to its health and vigour and to its interactions with other organisms. A general equation for photosynthesis is:

$$6\ CO_{2(gas)} + 12\ H_2O_{(liquid)} + \text{photons} \rightarrow C_6H_{12}O_{6(aqueous)} + 6\ O_{2(gas)} + 6\ H_2O_{(liquid)}$$

carbon dioxide + water + light energy → glucose + oxygen + water

A highly simplified summary of the respiration process is:

$$C_6H_{12}O_{6(aqueous)} + 6\ O_{2(gas)} \rightarrow 6\ CO_{2(gas)} + 6\ H_2O_{(liquid)} + \text{ATP (energy)}$$

It is characterized by light dependent oxygen consumption and the release of carbon dioxide.

The objective of this paper is exploring diurnal and annual cycles of the latent heat and CO_2 fluxes and temporal scale effects on the molecular carbon dioxide and water vapor diffusion and exchange processes at 6 different ecosystems in Southwestern North America.

2. DATA AND METHODOLOGY

Data were collected from AmeriFlux web page free downloads: http://cdiac.esd.ornl.gov/programs/ameriflux/data_system/aamer.html, for 6 sites inside the American Monsoon Area. The geographic range of sites varies in latitude from 29.95°N - 35.4°N and 97.99°W -111.77°W in Texas and Arizona American states. Automated micrometeorological measurements of CO_2 net flux (FC), latent (LE), sensible (H) and ground heat fluxes (G), air and soil temperature (Ta, Ts), wind speed and direction (W-S) and soil moisture (SWC) were taken over different vegetation landcovers. Experimental sites are monotypic ecosystems representative of regional vegetation. Figure 1 and table 1 describe the location and major features of each site. Carbon, water vapor, and energy fluxes were estimated with the eddy covariance technique from towers above the vegetation canopies. Flux systems comprised three axis sonic anemometers that measured wind-speed and virtual temperature, infrared gas analyzers that measured concentrations of water vapor and CO_2. Fluxes were averaged half-hourly.

Table 1. Explored eddy covariance sites in the North America monsoon area

Name	State	Registered period	Landcover
Santa Rita	Arizona	Jan. 2004 - Dec. 2006	30 % areal coverage mesquite 3-4 m high
Kendall	Arizona	May. 2004 - Dec. 2006	Warm season C4 grassland (bouteloua) with a few shrubs interspersed
Flagstaff Managed	Arizona	Jul. 2005 - Aug. 2006	Ponderosa pine forest
Flagstaff Unmanaged	Arizona	Sep. 2005 - Sep. 2006	Ponderosa pine forest in restoration
Flagstaff Wildfire	Arizona	Jun. 2005 - Aug. 2006	Ponderosa pine forest burned by a wildfire 11 years ago (1996), now the vegetation includes only herbaceous species and a few shrubs
Freeman Ranch	Texas	Jul. 2004 - Jul. 2006	Grassland in transition to an Ashe juniper-dominated woodland

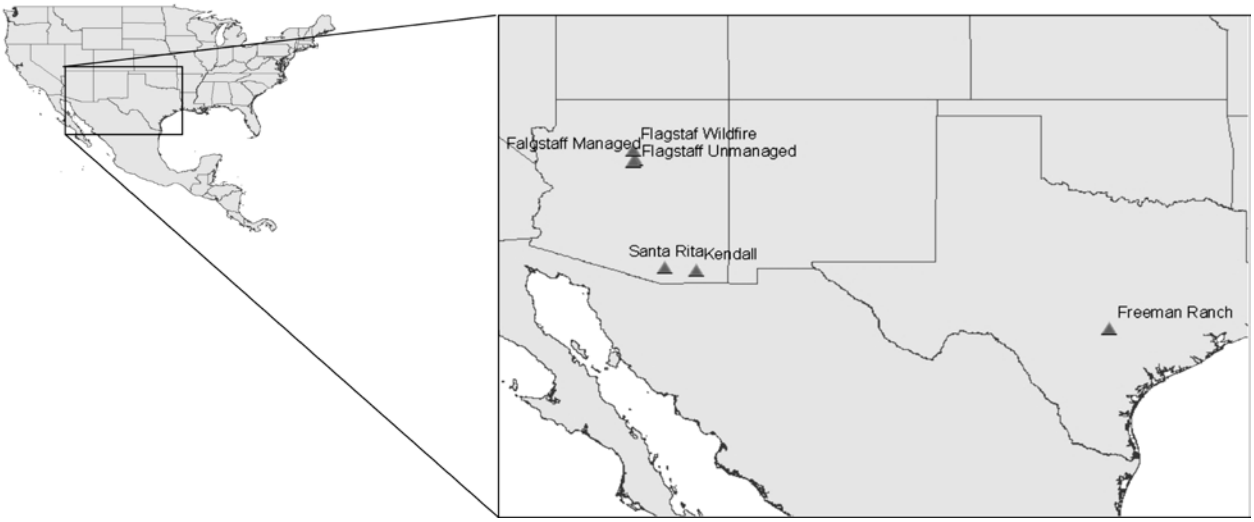

Figure 1. Explored eddy covariance sites in the North America monsoon area

3. RESULTS AND DISCUSSION

CO_2 AND LATENT HEAT FLUXES ABOVE THE CANOPY

Averaged 30 minutes CO_2 and latent heat fluxes time series above the canopy for all the ecosystems are showed in figure 2 at the same time period of Jul 1st - July 7th 2006 (7 daily cycles). Except by Santa Rita (30 % areal mesquite) and Kendall (graslands), general behavior reflects a considerable increase in the downward CO_2 flux (negative flux) with the upward increase of the latent heat flux in the daytime around noon, showing vegetal activity through diffusion processes of transpiration. Data from Santa Rita and Kendall illustrate an increasing behavior in the upward CO_2 flux with an increase in the latent heat flux, showing a convection (free and/or forced) effect which transports CO_2 away along with the flux of LE from the soil or poorly vegetated area.

ANNUAL CYCLES

To have a seasonal view of the data, probability distributions of the monthly quartiles were plotted using box-plots for each climatic station using daily averaged data. Each horizontal line inside the box shows the median of the distribution which gives an idea of the data asymmetry. Annual cycle for Santa Rita is showed in figure 3. Particular behaviors can be seen from each station. However, a whole pattern is described by the global radiation seasonal variation with extreme values in the days of the summer and winter Northern Hemisphere solstices. In whole, latent heat and CO_2 fluxes have a unimodal behavior with maximum/minimum values in the summer season, mostly in August-September showing a slight lag with the net radiation peak rate. Increase in net radiation, soil moisture, and high activity vegetation make CO_2 downward flux or net ecosystem exchange (NEE) to be in average 2 to 4 times larger in the monsoon season than in other months of the year, whereas LE could be as large as 10 times compared with the winter months. This explains formation of big cloudy systems which positively feedbacks the wet season. Such rates are obviously higher for the cases of the ponderosa forest and mesquite vegetation, which can be explained by the large vegetation activity in the summer season. Soil water content may be a controlling variable that shows a tendency of peak in summer at some stations and probably another peak at the ripening and melting phase of snow at the beginning of spring.

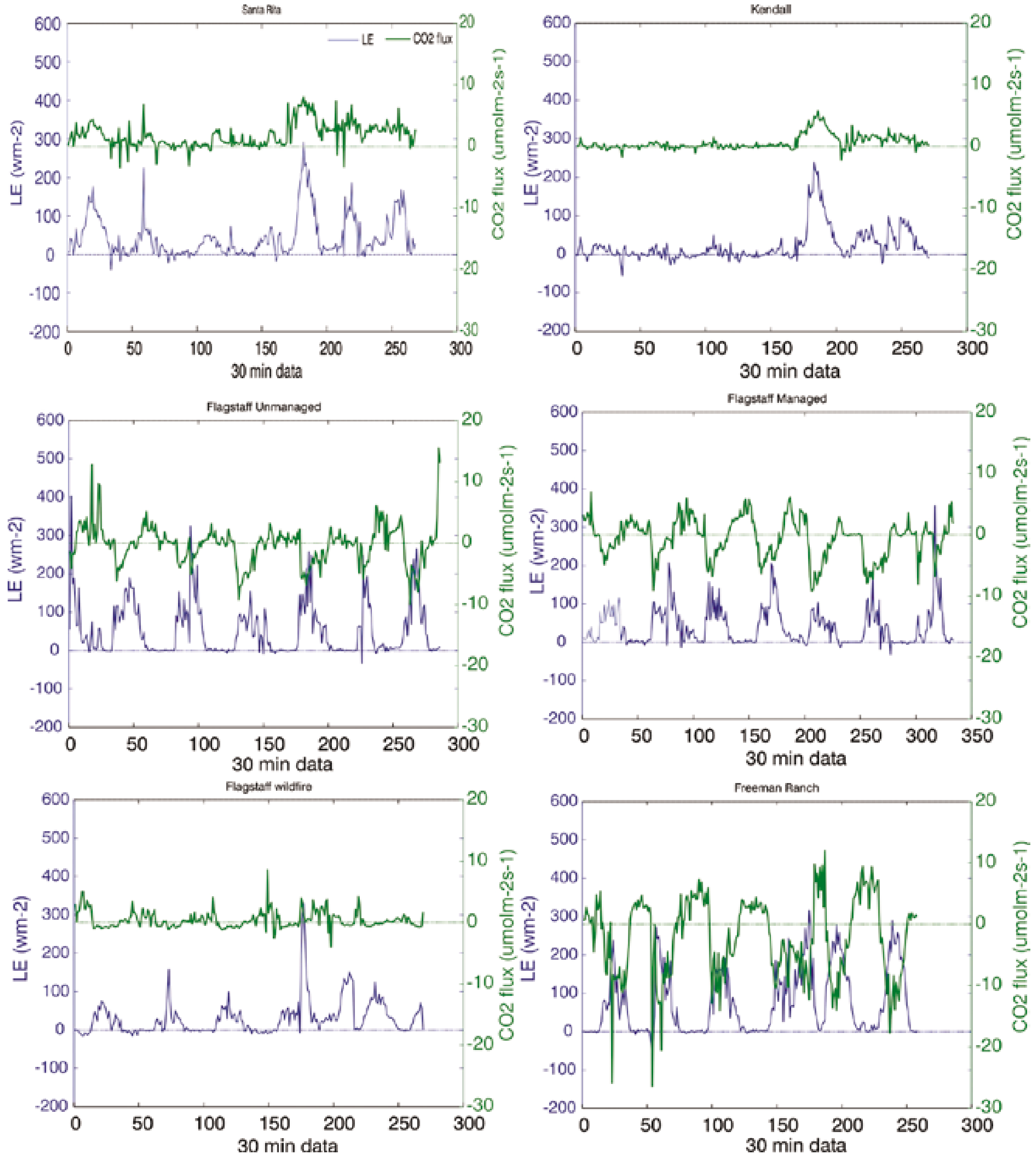

Figure 2. Averaged 30 minutes CO_2 and latent heat fluxes between July 1-7/2006 at all the sites

DAILY CYCLES

Daily cycles are becoming important in the scientific community, among other reasons, due to the possibility of having daily estimates of hydro-meteorological variables from instantaneous measurements (i.e. remote sensing images). Thereby, an analysis of the diurnal cycle may offer important information about the phase, amplitude, and influence of the radiation cycle and biophysical activity at that environment. Figure 4a and 4b illustrate the averaged daily cycles of CO_2 and latent heat fluxes for the six study sites. From figure 4a, phase of the maximum values are found to be between 11 a.m. and 1 p.m. according with the diurnal cycle of global radiation on the planet. A sine or cosine fitting process could be performed with the phase highly determined by solar zenith angle and a slight offset given by the mechanism of the transpiration process. High standard deviation from the main quartiles is found at noon or close to, due to the zenith angle seasonal variability or cloudiness during some days. From figure 4.b, according to the latent heat flux diurnal cycle, CO_2 flux shows a negative peak between 10 a.m. and 12 m. of each day. Such lag with respect to LE could be showing the optimal temperature effect for photosynthesis. However, flux rates are pretty similar during these three hours of the day. Again a sine wave could be fitted to this graph. The largest rates of CO_2 downward fluxes are accomplished at Flagstaff Unmanaged, Flagstaff Managed and Freeman Ranch. At these places, net ecosystem exchange at noon could be 5 times larger than in the afternoon, night or early morning.

CO_2 AND LATENT HEAT FLUX RELATIONSHIP TIME-SCALE DEPENDENCE

30 minutes time series

Latent heat flux and net ecosystem exchange are related through the carbon and energy balance equations. Specifically, this paper tries to answer the question: How much of the CO_2 net flux variability is explained by the latent heat flux at each site? Such exploration could lead us to identify an easy but strong relationship between the carbon fluxes and any other climatic or environmental measured variable. Hypothetically, if the surface under the eddy covariance station is well vegetated, diffusion process of the water vapor transpiration and CO_2 incorporation should have a strong negative correlation. Figure 5 shows such correlations with a significance statistical test. Bars with the small black circle on top mean enough statistical significance to consider valid the correlation. The statistical test uses a matrix of critical values p for testing the hypothesis of no correlation. Each p-value is the probability of getting a correlation as large as the observed value by random chance, when the true correlation is zero. If P(i,j) is small, less than the significance level $\alpha=0.05$, then the correlation R(i,j) is significant.

Table 2 summarizes the hypothesis test for the significance, $p<\alpha$, for the correlation coefficient on each of the time series with the CO_2 flux ($\alpha=0.05$). At this time scale, almost all the correlations are more significant than the purely random process with a probability of 95 %.

Valuable information may be extracted from the linear correlations. Both, Rn, LE and PAR have the strongest influence on the NEE process at this time scale. In fact, latent heat flux shows slightly higher correlations with CO_2 flux (FC), showing that it is probably the dominant predictive variable, mainly at vegetated landcovers, with correlations ranging between ~ -0.6 to ~ -0.8. Complementarily, LE depends on other variables as net radiation, sensible heat flux, ground heat flux.

Figure 6 shows an attempt to relate averaged net FC to LE at the 30 minutes time scale at all the sites. It is evident that steeper slopes and better fittings occur in the most vegetated zones (ponderosa forest and mesquite at Flagstaff unmanaged, Flagstaff managed and Freeman Ranch). Equations in table 3 show the fitting process and correlation coefficient for each site. The largest net primary production and the largest carbon sequestration should be occurring given the vegetation presence. Comparing the slopes

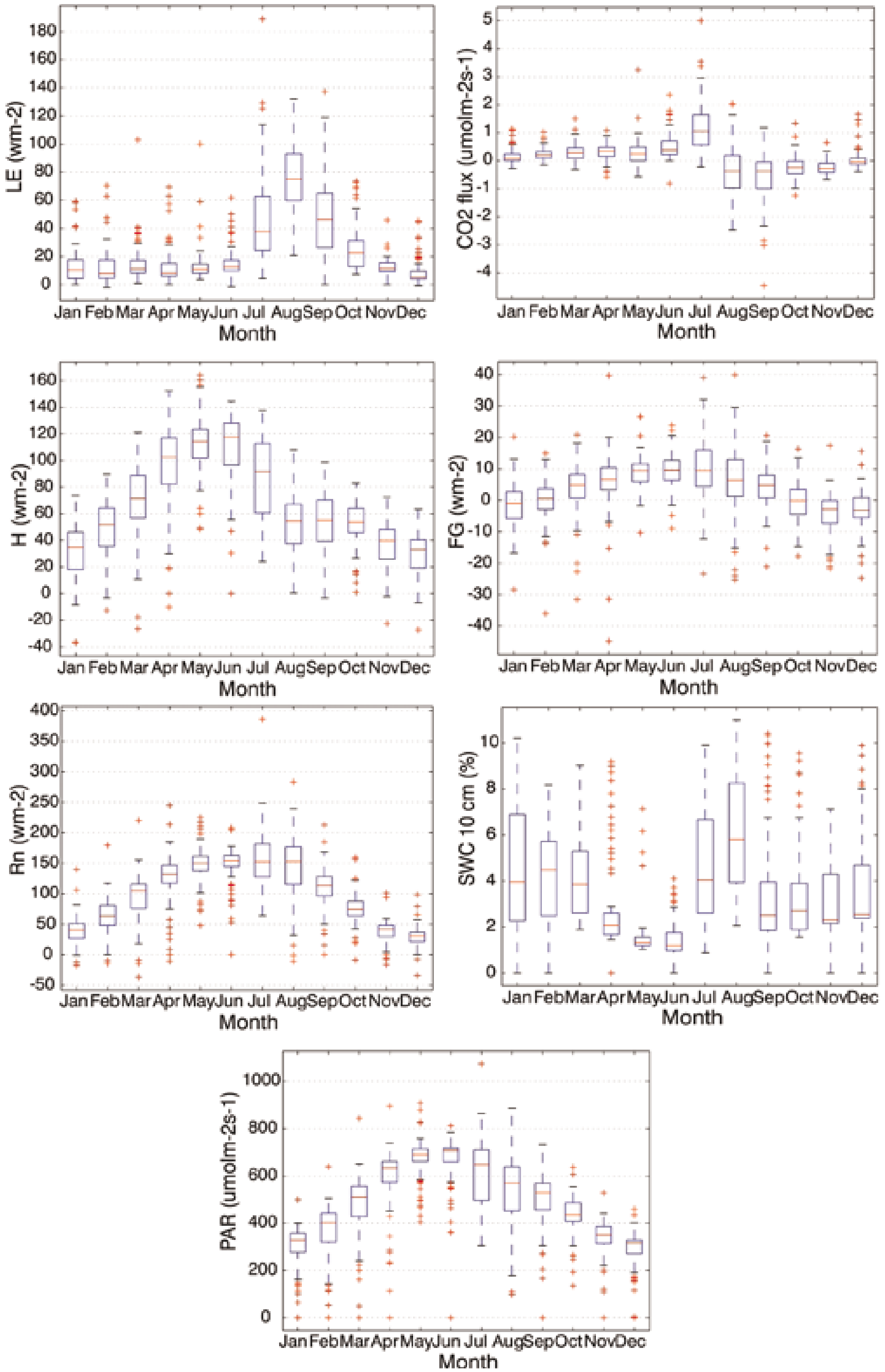

Figura 3. Annual cycles of the latent heat flux (LE), CO$_2$ flux (FC), sensible heat flux (H), ground heat flux (FG), net radiation (Rn), soil water content at 10 cm (SWC 10) and photosintetically active radiation (PAR) at Santa Rita site

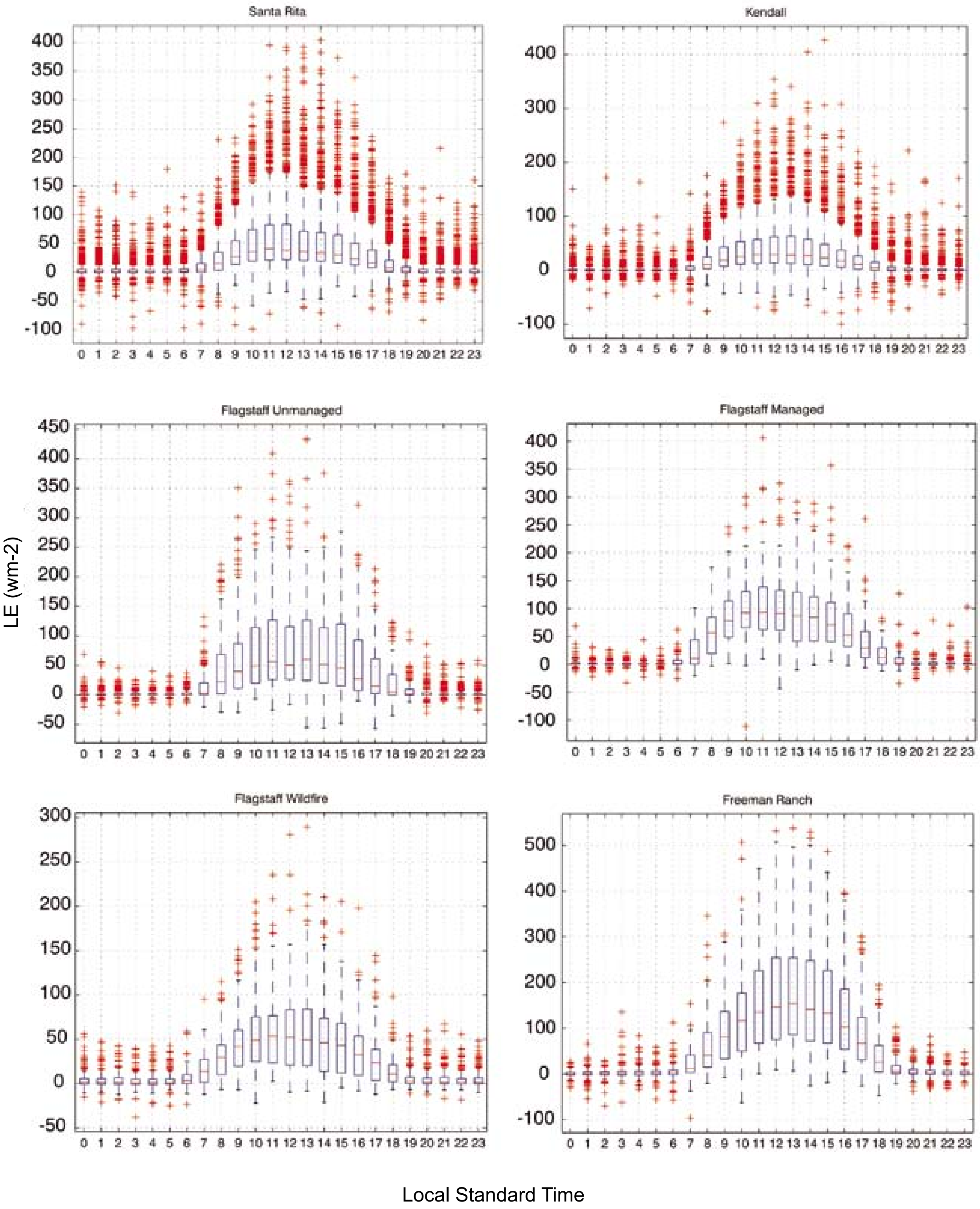

Figure 4a. Diurnal cycle probability distribution of the latent heat flux at the six eddy covariance sites

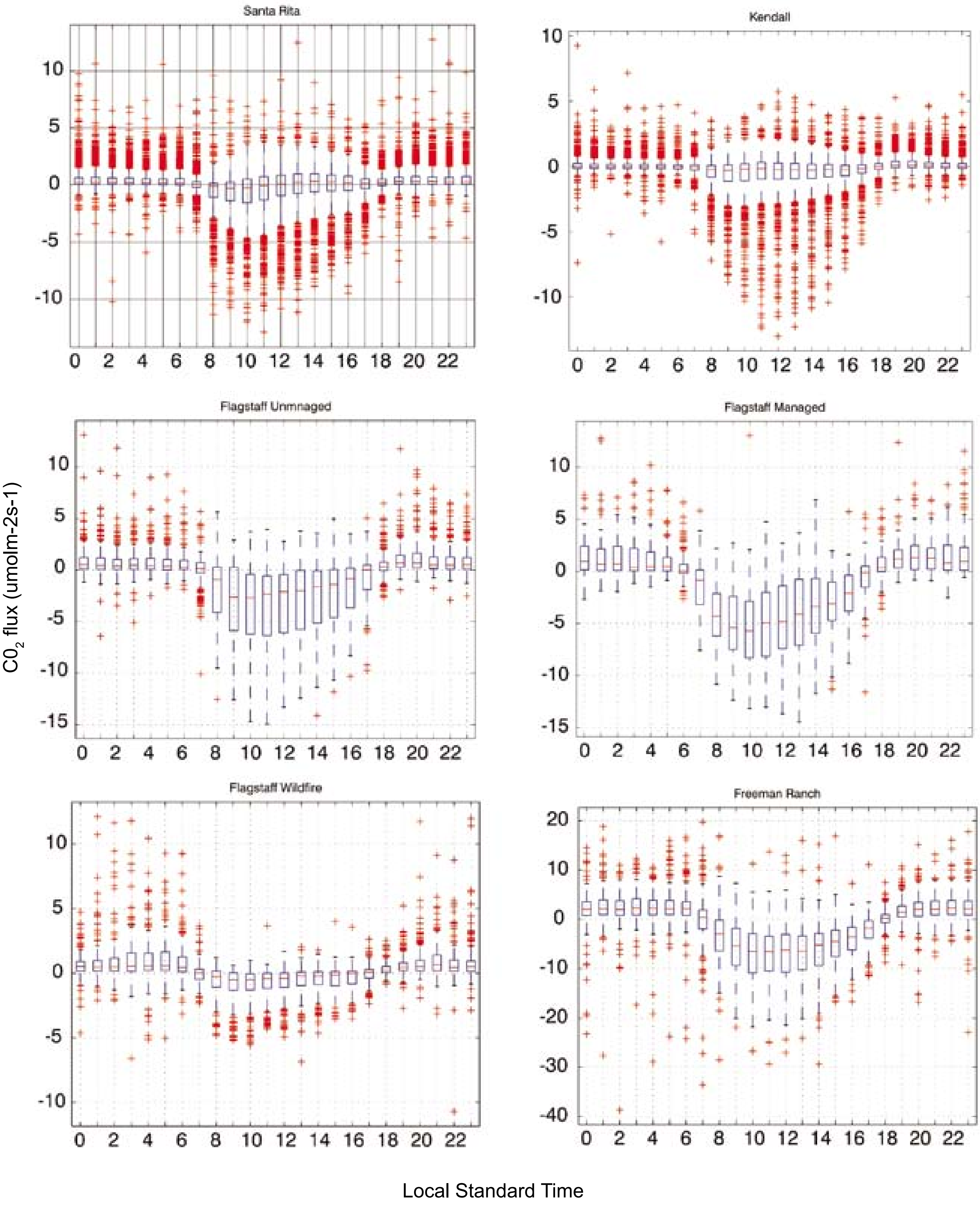

Figure 4b. Diurnal cycle probability distribution of the CO_2 flux at the six eddy covariance sites

and assuming a very similar proportion between net ecosystem exchange and net primary production we could say that forest is capturing carbon at a rate of approximately 3 times greater than the grasslands or bare soil at Santa Rita, Kendall or the Flagstaff land cover after the fire (wildfire).

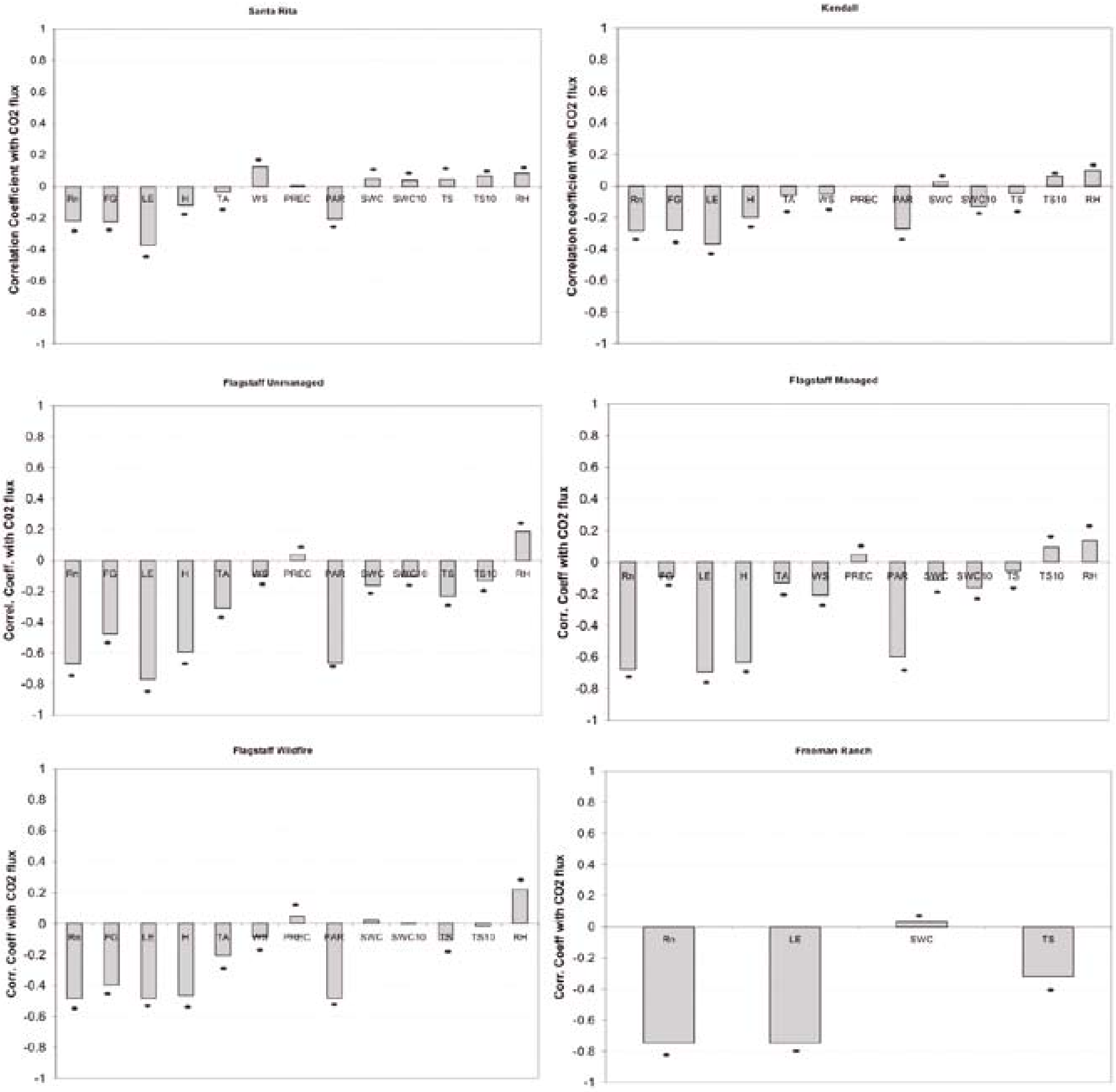

Figura 5. Cross correlations between CO_2 flux and any other measured variable at the 30 minutes resolution time scale

Table 2. CO_2 flux correlation matrix hypothesis tests

Site	Rejected correlation hypothesis test	Critical value, p Probability for random chance
Santa Rita	Prec	0.34
Kendall	--	--
Flagstaff Unmanaged	--	--
Flagstaff Managed	--	--
Flagstaff Wildfire	SWC, SWC_10, TS_10	0.03, 0.85, 0127
Freeman Ranch	--	--

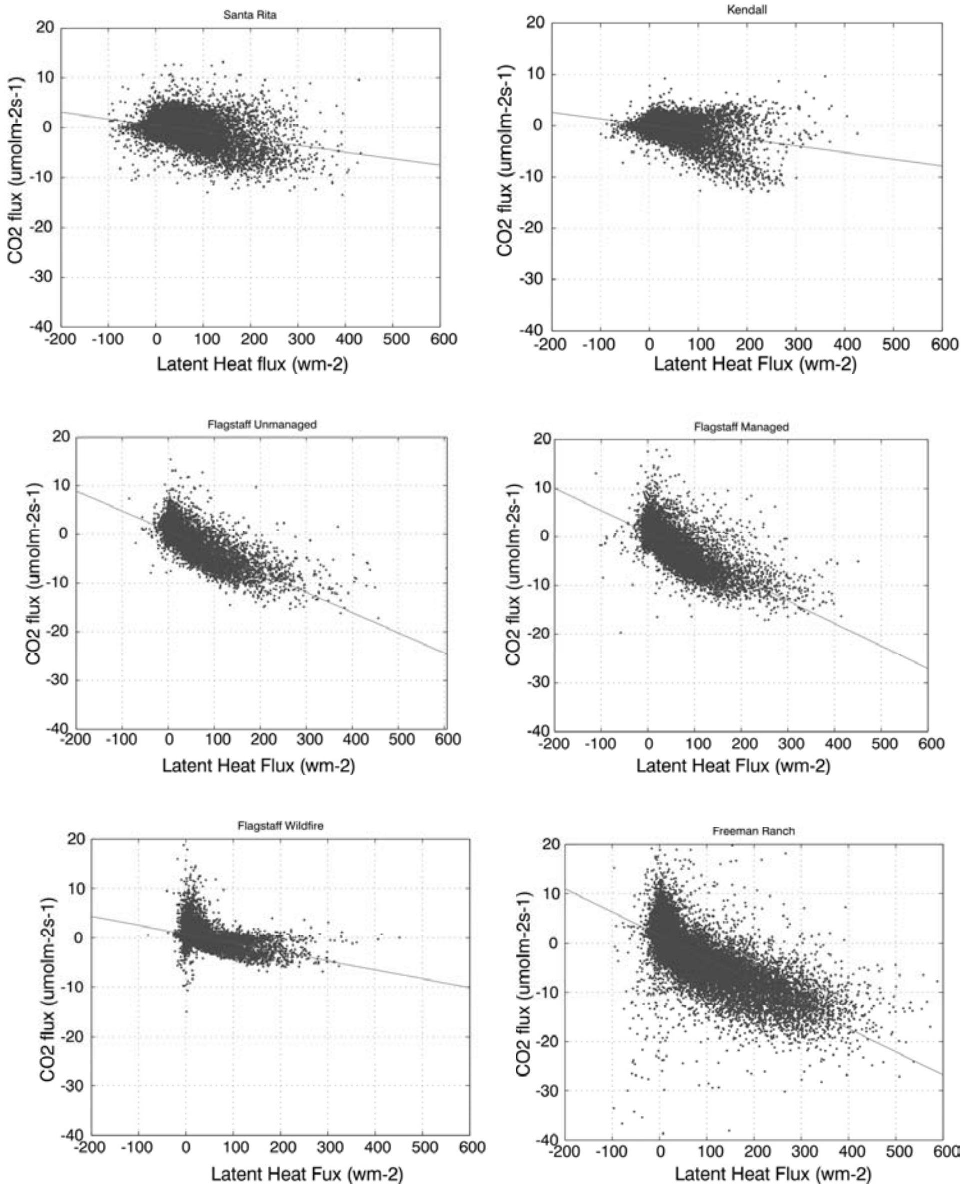

Figure 6. CO_2 flux and latent heat flux relationship for the 30 minutes data

Table 3. 30 minutes averaged fitting equations for FC and LE

Site	Fitted equation	Correlation coefficient
Santa Rita	FC=-0.013292LE+0.43885	-0.38
Kendall	FC = -0.013147LE + 0.02334	-0.37
Flagstaff Unmanaged	FC = -0.041706LE + 0.63112	-0.78
Flagstaff Managed	FC = -0.046409LE + 0.76362	-0.74
Flagstaff wildfire	FC = -0.018123LE+0.7456	-0.44
Freeman Ranch	FC=-0.047228LE+1.5283	-0.76

Daily scale

Averaging 30 minutes fluxes to daily scale we will observe if relations preserve or even if others appear. Table 4 shows the hypothesis test among CO_2 flux and any other variable. Now, many variables go out of the significant correlation, but still latent heat flux and net radiation have the maximum values at the highly vegetated stations. Figure 7 shows that the 30 min-scale linear tendency found at Santa Rita and Kendall is almost totally lost at the daily scale, which proofs that the effect of averaging fluxes could bring to misinterpretations of the fluxes occurring at finer time scales. Again it is evident that steeper slopes and better fittings occur in the most vegetated zones. Equations in table 5 show the fitting process and correlation coefficient for each site. Comparing the slopes and assuming a very similar proportion between net ecosystem exchange and net primary production we could say that the forest are having downward fluxes (uptake of carbon) in umol.$w^{-1}s^{-1}$ in average 6 times larger than the grasslands or bare soil at Santa Rita, Kendall or the Flagstaff land cover after fire (wildfire) at the daily time scale.

Monthly scale

Figure 8 as well as table 6 illustrate the same procedure for the time series aggregated at the monthly scale. Basically, the most significant variables in determining CO_2 fluxes are net radiation and latent heat flux. Going back again at the CO_2 vs LE figures, slope relationship between the forest and mesquite vs grasslands and bare soils show that rates of carbon uptake for photosynthesis, in average 2 times larger, are found in the most vegetated environments. As expected, an increase in the net radiation and soil water content in the monsoon season leads to an increase in the rate of evapotranspiration and, as a consequence, in the net CO_2 exchange ecosystem.

Table 4. CO_2 correlation matrix hypothesis tests

Site	Rejected correlation hypothesis test	Critical value, p Probability for random chance
Santa Rita	LE, Prec, RH	0.16, 0.08, 0.9
Kendall	H, TA, WS, TS, TS_10, RH	0.88,0.47, 0.38, 0.77, 0.19, 0.08
Flagstaff Unmanaged	WS, Prec, RH	0.74, 0.14, 0.18
Flagstaff Managed	FG, TA, WS, Prec, TS, TS10, RH	0.71, 0.77, 0.3, 0.08, 0.77, 0.72, 0.75
Flagstaff wildfire	WS,SWC10	0.91, 0.40
Freeman Ranch	SWC	0.1

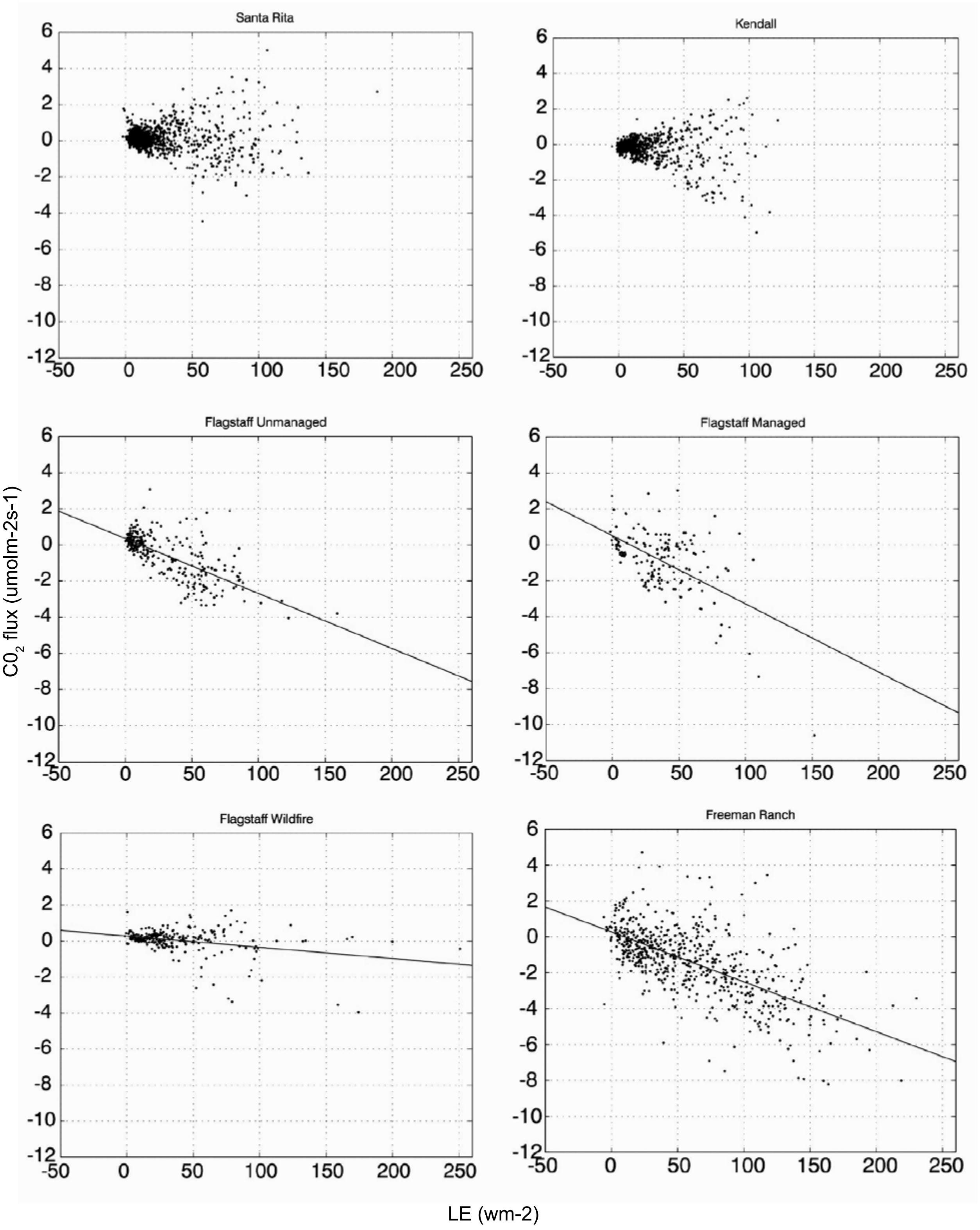

Figure 7. CO$_2$ flux and latent heat flux relationship at the daily scale

Table 5. Daily scale fitting equations for FC and LE

Site	Fitted equation	Correlation coefficient
Santa Rita	FC=-0.0011558LE+0.16685	-0.03
Kendall	FC= -0.005499LE-0.085711	-0.2
Flagstaff Unmanaged	FC=-0.030387LE+0.35189	-0.7
Flagstaff Managed	FC=-0.037879LE+0.50133	-0.57
Flagstaff wildfire	FC=-0.0062427LE+0.2751	-0.32
Freeman Ranch	FC=-0.027773LE+0.27023	-0.64

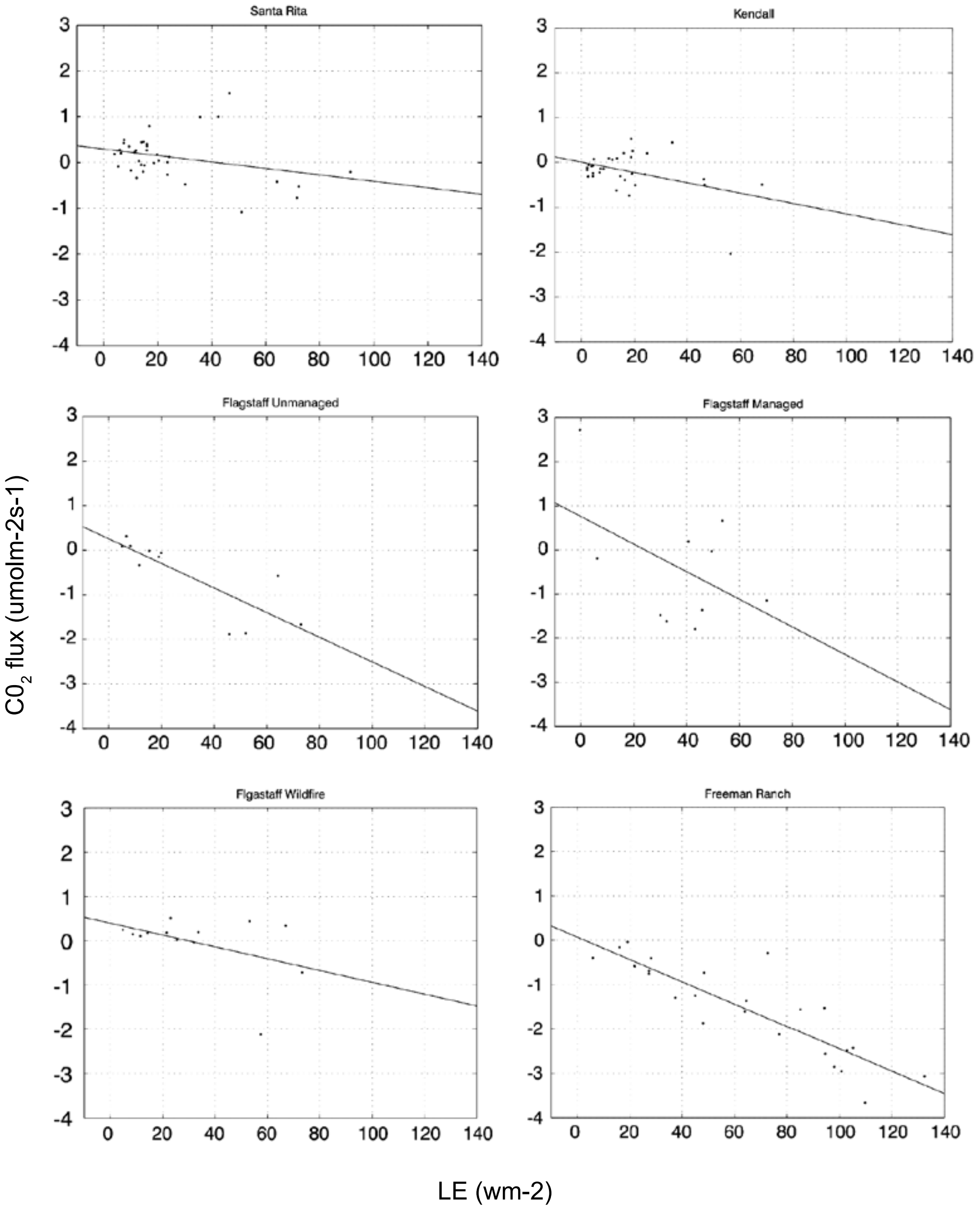

Figura 8. CO$_2$ flux and latent heat flux relationship at the monthly scale

Table 6. Monthly scale fitting equations for FC and LE

Site	Fitted equation	Correlation coefficient
Santa Rita	FC=-0.00741LE+0.29232	-0.3
Kendall	FC=-0.011537LE+0.0071311	-0.42
Flagstaff Unmanaged	FC=-0.027592LE+0.25528	-0.79
Flagstaff Managed	FC=-0.031282LE+0.75893	-0.48
Flagstaff wildfire	FC=-0.01334LE+0.39668	-0.42
Freeman Ranch	FC=-0.025214LE+0.071645	-0.84

4. CONCLUSIONS

Highly vegetated areas show higher influence of the diffusion transpiration process on the CO_2 downward rates establishing a high negative correlation between the latent heat and the net ecosystem exchange.

Poorly vegetated zones exhibit smaller negative correlations and convection processes of CO_2 involved with the upward latent heat fluxes which makes less efficient the process of carbon up taking by the few vegetation landcover.

Latent heat and CO_2 fluxes have a unimodal behavior with maximum values at the summer season, mostly in August-September showing a slight lag with the net radiation peak rate. Large net radiation, soil moisture, and activity vegetation make CO_2 30 minutes averaged downward flux or net ecosystem exchange (NEE), to be in average 2 to 4 times higher in the monsoon season than in other months of the year, whereas LE could be as large as 10 times compared with the values for other months. This explains formation of big cloudy monsoon systems. Such rates are obviously higher for the cases of the ponderosa forest and mesquite vegetation.

CO_2 flux diurnal cycle shows a negative peak between 10 a.m. and 12 m. each day. Such lag with respect to LE could be related to the optimal temperature for photosynthesis. The largest rates of CO_2 fluxes are accomplished at Flagstaff Unmanaged, Flagstaff Managed and Freeman Ranch. At these places, net ecosystem exchange at 10 a.m. could be 5 times larger than in the afternoon, night or early morning.

At almost all the explored time scales LE explains more than 50 % of the variability of the NEE in the studied highly vegetated zones. At the 30 minutes time scale a nice straight line could be adjusted between CO_2 flux and latent heat flux at forests and other highly vegetated places since transpiration increases. The net uptake of carbon for the photosynthetic processes ($\mu mol.m^{-2}.s^{-1}$) could be at least 3 times greater than that found in grasslands, wildfire, or bare soil landcover.

The effect of aggregating time series to larger time-scales is smoothing values but the most important correlations preserve.

At daily and monthly scales evapotranspiration and CO_2 net flux could also be controlled by the net radiation, which has a direct influence on PAR, latent heat flux, and soil moisture, which at time could be controlling LE especially in the monsoon season. Further studies should be conducted showing the seasonal variability of LE and CO_2 flux and soil water content effects and consequences for modeling this process in tropical and extratropical areas.

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