

SEASONAL CO₂ FLUXES AND ENERGY BALANCE IN A KIWI FRUIT ORCHARD

FLUSSI DI CO₂ E BILANCIO ENERGETICO STAGIONALE IN UN IMPIANTO DI ACTINIDIA

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Abstract

This study reports the seasonal assessment of energy balance components and carbon dioxide fluxes over a drip irrigated kiwifruit orchard, with a Leaf Area Index (LAI) of 3 at full canopy development. The most remarkable amount of energy partitioning throughout the whole season was due to latent heat flux that had values approximating to those of sensible heat flux (about 200 W m⁻² s⁻¹ at midday) only in May, when leafy biomass was still developing. From June to September, latent heat flux kept constantly at about 50% of net radiation (R_n), and did not appear to be influenced by the air temperature, very high in its maximum values during the three months of June, July, August. Canopy carbon assimilation reached maximum values of about -14 μmol m⁻² s⁻¹ during May and June, and values decreased in July and August respectively to -12 and -10 μmol m⁻² s⁻¹, turning to -13 μmol m⁻² s⁻¹ again in September. Going on with the season, a marked decrease of the canopy photosynthesis was observed. A diurnal decline in photosynthesis similar to that recorded from single leaf measurements is reported and an amount between 60% and 75% of the total carbon is fixed by the orchard in the morning between 7 and 12.30. The seasonal timing and the amplitude of the net system carbon flux as well as the ones of the components fluxes corresponding to assimilatory and respiratory processes has been quantified. The Net Ecosystem Exchange (NEE) of the kiwifruit system was at around 3 t of carbon during the seven months leafy period (useful to produce 12.5 t total biomass ha⁻¹, more than 50% partitioned to perennial structures), when 8.5 t of carbon were lost in ecosystem respiration. Such fluxes are the sum of contribution to both kiwifruit plants and cover crop, present during all the season.

Daily and seasonal canopy water use efficiency (WUE) is also reported. Midday averaged monthly values indicate that WUE is 0.0027 and 0.0029 in May and June respectively, and decreases to 0.0022 in July up to a minimum of 0.0018 in August. WUE values increase after that time reaching higher values in September (0.0033) and October (0.0046). In each month, the diurnal trend shows constant higher water use efficiencies in the morning hours, evidently matching the photosynthetic daily patterns.

Keywords: Kiwifruit, eddy covariance, radiation partitioning, carbon dioxide exchanges, net ecosystem exchange.

Riassunto

In questo studio vengono riportate le stime dei componenti del bilancio energetico e dei flussi di biossido di carbonio in un actinidiario irrigato a goccia che al momento del suo massimo sviluppo vegetativo aveva un LAI di 3. L'apporto più consistente nella partizione energetica durante l'intera stagione vegetativa, è stato dato dal calore latente, che solo nel mese di maggio riportava valori simili a quelli del calore sensibile (circa 200 W m⁻² a mezzogiorno) mentre la biomassa fogliare era ancora in fase di accrescimento. Da giugno a settembre il calore latente si è mantenuto costantemente su valori corrispondenti a circa il 50% della R_n, senza essere apparentemente influenzato dalla temperatura dell'aria veramente alta nei suoi valori massimi durante i mesi di giugno, luglio e agosto. L'assimilazione del carbonio ha raggiunto un valore massimo di -14 μmol m⁻² s⁻¹ in maggio e giugno calando a -12 e -10 μmol m⁻² s⁻¹ rispettivamente in luglio e agosto, e tornando nuovamente a -13 μmol m⁻² s⁻¹ in settembre. Si è osservato un declino diurno nella fotosintesi, così come misurato su singole foglie, inoltre è stato rilevato che nelle ore comprese tra le 7 e le 12.30 il frutteto ha fissato tra il 60 ed il 75% del carbonio totale. Sono stati quantificati gli andamenti stagionali e le dimensioni dei flussi netti di carbonio nelle componenti assimilative o respiratorie. La NEE dell'actinidiario è stata di circa 3 t di carbonio durante il periodo vegetativo (capace di produrre 12.5 t di biomassa totale ha⁻¹ più del 50% della quale allocata in strutture perenni), mentre 8.5 t di carbonio sono stati consumati dai processi respirativi. Tutti i suddetti flussi sono avvenuti con il contributo sia del frutteto che della vegetazione dell'inerbimento presente durante tutte le stagioni.

È stato calcolato anche il WUE giornaliero e stagionale. Il valore medio mensile misurato a mezzogiorno è stato di 0.0027 e 0.0029 rispettivamente in maggio e giugno, è decresciuto a 0.0022 in giugno raggiungendo un minimo di 0.0018 in agosto. In seguito il valore dell'WUE è aumentato raggiungendo i valori massimi in settembre (0.0033) e ottobre (0.0046). In tutti i mesi il trend diurno del WUE ha mostrato valori più elevati nelle ore mattutine, in accordo con l'andamento della fotosintesi.

Parole chiave: Actinidia, eddy covariance, partizione radiativa, scambi di biossido di carbonio, scambio netto dell'ecosistema.

Introduction

The energy and carbon exchanges between the terrestrial vegetation and the atmosphere are the result of complex atmospheric and ecophysiological processes that regulate biophysical fluxes at the surface. Information on such exchanges are needed to understand how the atmospheric CO₂ concentration varies in space and time and, on a global scale, questions arise about knowing the location of carbon and water vapour sources and sinks and their specific strength. Diurnal, seasonal and yearly dynamics and the possible variations induced by environmental perturbations and land use are also primarily considered (Baldocchi *et al.*, 2000; Weaver and Avissar, 2001).

The temporal pattern of energy partitioning between latent and sensible heat is dependent on the fluctuating interactions between available radiation, air temperature, humidity, atmospheric vapour pressure deficit and the ability of the plants to evapotranspire and supply water to the surrounding atmosphere. Diurnal evapotranspiration trends are controlled by ecophysiological responses to environment through the regulation of stomatal conductance (Jarvis and McNaughton, 1986), as well as diurnal patterns of atmospheric demand are primarily dominated by the movement of the sun and the evolution of the planetary boundary layer (Chambers and Chapin, 2002; Patton *et al.*, 2003). The interception and the use of sunlight from the leaves, assembled into different layers and having different orientation, to assimilate carbon dioxide is at the basis of the canopy photosynthesis. Structural canopy characteristics act in association to physiological interactions with the atmosphere in regulating the diurnal pattern of net carbon flux (Ross, 1981; Myneni *et al.*, 1989; Norman and Polley, 1989).

Biosphere-atmosphere interaction measurement and modelling involves, together with agrometeorologists, different scientific communities. Atmospheric physicists need to quantify surface fluxes at the land-atmosphere interface as the energy partitioning is determinant on weather and climate (Pielke *et al.*, 1998). Ecology scientists aim to assess the flows of energy, carbon, water to and from the biosphere for different ecosystems under different climate, environment and soil conditions, space and time scales (Baldocchi, 1997; Goldstein *et al.*, 2000; Meyers, 2001). Similarly, horticultural community merges specific interests in understanding cultivated plants ecophysiology to minimize the human impact, concomitantly maximizing the local environmental resources. The new concern about long-term agricultural sustainability require to bridge the long-standing gap between ecology and agronomy, and new approaches imply interdisciplinary knowledge, involving contributions by horticulture, physiology, ecophysiology, meteorology, and micrometeorology (Rossi, 2006).

The assessment of carbon fluxes offers a useful tool for understanding the carbon economy of plants (Chen *et al.*, 2003; Wang *et al.*, 2004) and has the potential to determine the atmospheric carbon dioxide sink effect of horticultural crops. The dynamics of energy balance partitioning in orchards is in fact scarcely known (Baldocchi and

Hutchinson, 1988; Georgiadis *et al.*, 1992; Georgiadis *et al.*, 1996; Rossi *et al.*, 1996; Braun *et al.*, 2000; Spano *et al.*, 2000), and very few observations have been reported on seasonal CO₂ fluxes on different fruit tree species (Rossi *et al.*, 2004, Pernice *et al.*, 2006). For natural ecosystems, a growing amount of information comes for a wide range of functional types and climates from FLUXNET, a worldwide network of stations measuring the diurnal and seasonal exchanges of carbon dioxide, water and energy fluxes. At present, 200 sites are operating on a long-term and continuous basis on five continents, with a latitudinal distribution ranging between 70°N to 30°S, and vegetation under study includes temperate conifer and broadleaved deciduous and evergreen forests, short crops, grasslands, chapparal, wetlands and tundra. Data are used to quantify and compare magnitudes and dynamics of annual ecosystem carbon and water balances, to understand the response of stand-scale carbon dioxide and water vapour flux densities to control biotic and abiotic factors, and to validate a hierarchy of soil-plant-atmosphere trace gas exchange models (Baldocchi *et al.*, 2001; Wilson *et al.*, 2003). This network also provides ground information for validating estimates of primary productivity, energy absorption and evapotranspiration being generated by satellite sensors (Running *et al.*, 1999).

The common methodology adopted in FLUXNET network is the eddy covariance, that allows a continuous assessment of latent, sensible heat and carbon fluxes on hourly, daily, seasonal temporal scales and at the spatial scale of plant stands. This same micrometeorological technique has been utilized in this study for a kiwifruit orchard exchange monitoring, since it is recognized to be the most suitable in studying whole-canopy physiology. For fruit trees, in fact, net carbon exchanges and plant water relations have been so far studied through leaf cuvettes, widely used to assess the diurnal variation of photosynthesis and define environmental response functions for different species and agronomic managements also under different field conditions (Lakso *et al.*, 1999; Rosati *et al.*, 1999), and whole-plant enclosures (Giuliani *et al.*, 1997). Thus, leaf and canopy evapotranspiration and photosynthesis investigations are impaired by a lack of coupling between plant and boundary layer atmospheric processes.

This study reports the seasonal assessment of energy balance components and carbon dioxides fluxes over a kiwifruit orchard. Actinidia is a perennial climbing species successfully grown in both continental and maritime environments. Native to China, kiwifruit has been extended since the beginning of the 20th century in many areas of the globe, and its relevance has been progressively increasing due to the acknowledged nutritional value also based on high contents of vitamin C and to its ability to protect DNA in the nucleus of human cells from oxygen-related damages (Collins *et al.*, 2001).

Italy is the highest producer, followed by New Zeland, Chile, USA, Japan and France. The progressive increase in the areas of land planted in kiwifruit in many Coun-

tries of different continents in the last few decades brought with it a demand for information on all the aspects of the crop management, and the assessment of the physiology and water relations of this species have been object of many measurements and modelling efforts, leading to high degree of specific knowledge. As for the other fruit trees, most studies have focused on either leaf (Buwalda *et al.*, 1991; Gucci *et al.*, 1996) or whole canopy gas exchanges, both with measurement and modelling approaches (Buwalda *et al.*, 1992b; Buwalda *et al.*, 1993). No information about whole canopy fluxes has been so far reported in the literature for this species. Since kiwifruit needs high irrigation water inputs, the temporal assessment of the energy used for evapotranspiration processes can be particularly meaningful also for agronomical applications (Testi *et al.*, 2004).

Materials and Method

The orchard and the vine characteristics

Measurement have been carried out during 2003 growing season in a thirteen-years-old kiwifruit [*Actinidia deliciosa* (A. Chev.) C.F.Liang et A.R. Ferguson] cv. Hayward orchard trained at a T-bar trellis system under standard commercial management. The orchard was located in a flat area of the Po plane at S.Pietro in Vincoli (Ravenna, Italy), 45°28'N, 11°27'E, and covered an extension of 18 ha. The spacing was 2.5 m within rows and 5 m between rows, with a consequent allocated 12.5 m² of land per vine, and the female/male ratio was 8:1. Canopy height at full cover reached 1.9 m.

Drip irrigation was at a constant daily rate of 4.5 mm/day throughout the entire season till to harvest with a total 45 m³ ha⁻¹ water distributed daily. Cover crop in the row and inter-row spaces was maintained at a minimum height (about 4 cm) by regular topping.

Shoot elongation and leaf expansion were followed in 50 shoots randomly chosen in 25 different vines, and LAI temporal evolution was directly determined.

Ten shoots were destructively sampled at about once a week from budbreak to harvest to monitor the fresh weight and the water content (determined after desiccation at 80°C till to constant weight) of the shoot axis, of leaves and fruits when present.

At harvest, production was recorded by direct harvesting twenty single vines.

Flux instrumentation and monitoring

Continuous half-hourly CO₂, heat and evapotranspiration fluxes have been measured over the orchard surface using the eddy covariance technique starting from budbreak till to leaf fall.

Wind velocity and temperature fluctuations were measured with a three dimensional sonic anemometer (Metek GmbH, USA1, Elmshorn, Germany), and water vapour and carbon dioxide with an open-path, infrared absorption gas analyser (IRGA Li7500. LiCor Inc, Lincoln, NE, USA). The IRGA was kept calibrated as recommended in the LICOR instruction manual. Quality controlled eddy covariance measurements of evapotranspiration and CO₂ had an error of approximately 3% prior to correction.

Tab. 1 – Structural characteristics of the kiwifruit vines.

Tab. 1 – *Caratteristiche strutturali dei germogli di actinidia*

| Average shoot number | Average cane number | Average vine shoot number |
|----------------------------|-------------------------------|-----------------------------|
| 11 | 17 | 187 |
| Vine shoot number (<50 cm) | Vine shoot number (50-150 cm) | Vine shoot number (>150 cm) |
| 105 | 62 | 20 |

Tab. 2 – Components of yield of the orchard.

Tab. 2 – *Alcune componenti del frutteto*

| Record | Mean | St.error |
|-------------------|------|----------|
| Trunk girth (cm) | 9 | 2 |
| Buds/cane (n) | 22.6 | 1.2 |
| Budbreak (%) | 69 | 2 |
| Flowers/shoot (n) | 6.85 | 0.34 |
| Flowers/bud (n) | 4.27 | 0.27 |

Tab. 3 – Calculated dry biomass distribution of the orchard (fruit yield=12.5 t ha⁻¹) following Buwalda and Smith (1987). In brackets are the values measured for our orchard.

Tab. 3 – *Calcolo della distribuzione della biomassa (peso secco) nel frutteto (produzione =12.5 t ha⁻¹) secondo Buwalda e Smith (1987). Tra parentesi i valori misurati nel nostro frutteto.*

| | Dry biomass (t/ha) | Total (%) |
|----------------------|----------------------|------------|
| leaves | 1.35 (1.91 measured) | 10.8 |
| Fruit | 2.65 (2.50 measured) | 21.2 |
| Shoots | 1.42 (1.35 measured) | 11.4 |
| Laterals | 1.03 | 8.3 |
| Cordon | 0.39 | 3.1 |
| Stem | 0.50 | 4.0 |
| Structural roots | 4.11 | 32.9 |
| Fibrous roots | 1.02 | 8.2 |
| Total biomass | 12.47 | 100 |

Data were sampled at 10 Hz and stored on a portable PC using MeteoFlux software (Servizi e Territorio s.r.l, Cinisello Balsamo, Italy), and eddy covariance post-processing was performed to obtain 30 minutes averages of fluxes.

These instruments were positioned at 4.2 m from the ground on a mast located in a central position of the orchard.

On the same pole was disposed a CNR1 net radiometer (Kipp and Zonen, Delft, NL), separately measuring incoming and outgoing short-wave and long-wave radiation every 10 seconds, averaging every 30 minutes and storing data on a CR10 Campbell data logger. A second CNR1 radiometer was located below the canopy at 1.6 m from the ground.

Heat storage in the soil was measured through three soil heat flux plates inserted at a deep of 10 cm at in three radial positions at the same distance (200 cm) from the girth of the cane closer to the must.

During the eddy covariance monitoring, a one-week experiment was settled in July to measure photosynthesis and nocturnal respiration at shoot level. A well exposed, unshaded shoot was sealed into a 9.5 l volume Teflon bag. Flow rate of incoming air into the bag was kept at 11 l/min, and internal temperature was measured by a semi-conductor temperature sensor LM35CZ (National Conductor, Santa Clara, CA, USA). The CO₂ flux was recorded by a ADC 2250 (Bioscientific Ltd., Hoddesdon, UK) operating in differential mode, and data were stored into a portable pc. The total area of the enclosed leaves was measured at the end of the experiment.

Results and Discussion

Phenology and plant growth

Budbreak was on April 6, flowering started on May 21 (50% flowers open on May 25), harvest at October 17, and leaf senescence and abscission commenced at the beginning of November, being the third week of November the time of full leaf fall.

Structural characteristics of the kiwifruit plants were calculated by non-destructive direct phytometric measurements, that allowed to discriminate different trends of growth in relation to the type of shoot, and hence to reconstruct canopy biomass growth with a high degree of accuracy.

Tab. 1 and 2 respectively summarize the structural features of the vines and the main components of yield. 56% of total shoots (current season's growth) were characterized by the absence of the terminal bud and hence were limited in growth. Such a kind of spurs (known as terminating shoots) reached their final length, lower than 50 cm, at the very beginning of June. 33% of the others, non terminating shoots, had a steep elongation trend in the first stage after budbreak, followed by a continuously slowing growth pattern till they reached their maximum length, lower than 150 cm, at the end of July. The other 11% shoots reached more than 150 cm in length and their elongation trend was maximum and nearly constant at 3.5 - 4 cm day⁻¹ during all the month of June. A subsequent sharp decrease in growth was registered during the first two weeks of July, when the growth of biomass definitely terminated (Fig.1). Total leaf area per vine reached its maximum of about 37 m² at this time (Fig. 2), with the mean leaf size increasing up to a plateau at 4 weeks after budburst. The total leaf area index (m² leaf area m⁻² apportioned orchard area) arrived to the final value of 3. The temporal increment of the leafy biomass was concomitant to a progressive increase of the aerodynamic roughness of the orchard, evidenced by the trend of the surface roughness length z₀, that reached its maximum values of about 0.8 when canopy was fully developed (Fig. 3).

Total dry biomass partitioning was derived by applying the percentages reported in Buwalda and Smith (1987) for typical mature kiwifruit vines with known fruit yield (Tab.3). The calculated total fruit dry matter appeared very congruent with the measured values (2.65 t ha⁻¹ with respect to 2.50), as was that allocated to shoots (1.42 t ha⁻¹ in comparison to 1.35) and leaves (1.91 in comparison to 1.35). Thus, it came out a very plausible

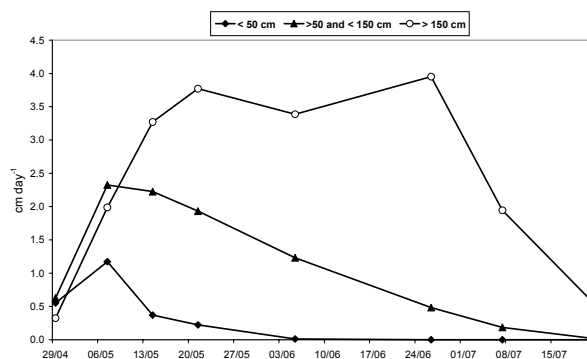


Fig. 1 – Seasonal daily growth rate of the shoots grouped according to their final length.

Fig. 1 – Tasso di allungamento dei germogli raggruppati in classi di lunghezza finale.

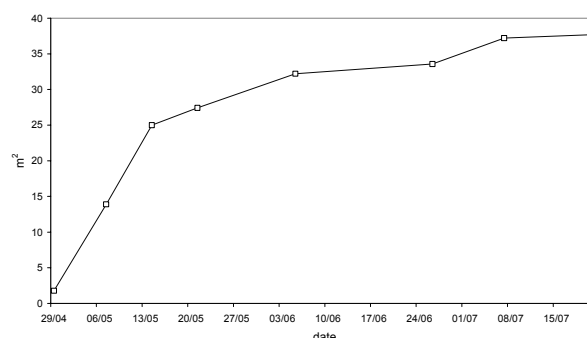


Fig. 2 – Temporal trend of the total leaf area of a single vine during the growth period.

Fig. 2 – Andamento temporale dell'area fogliare totale in un singolo germoglio durante il periodo di crescita.

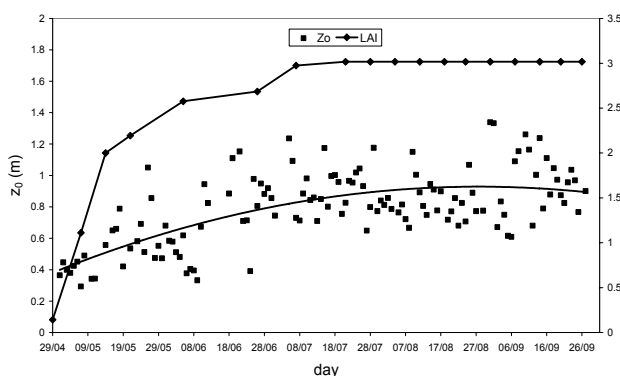


Fig. 3 – Seasonal evolution of leaf area index (LAI) and of the surface roughness length (Z₀).

Fig. 3 – Evoluzione stagionale dell'indice di area fogliare (LAI) e della rugosità superficiale (Z₀).

chance to infer the biomass distribution of the orchard into the other components according to the scheme proposed above (Tab.3). The root (structural plus fibrous) biomass of our orchard resulted about 5 t dry matter ha⁻¹, and the total biomass produced was at around 12.5 t ha⁻¹.

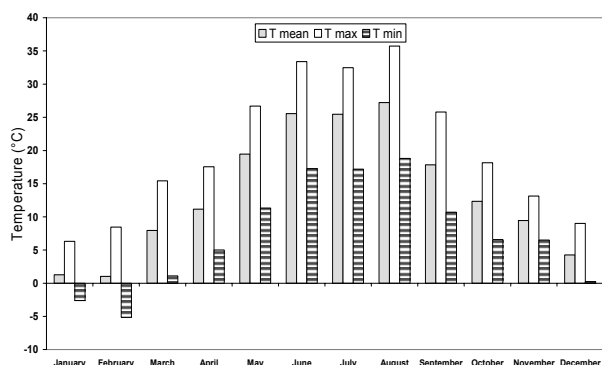


Fig. 4 – Monthly mean, maximum and minimum air temperature recorded in the year of measurements.

Fig. 4 – *Temperatura media, massima e minima dell'aria registrata nel periodo di misure.*

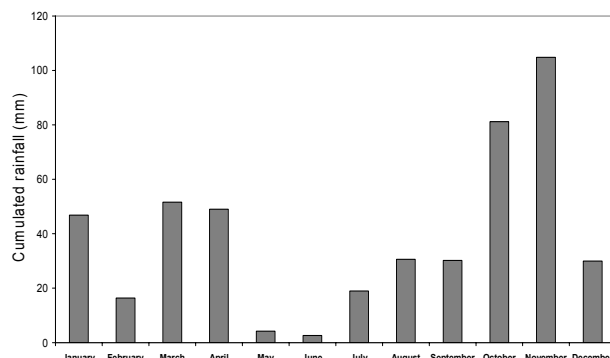


Fig. 5 – Monthly cumulated rainfalls in the year of measurements.

Fig. 5 – *Precipitazioni mensili cumulate nell'anno di misura.*

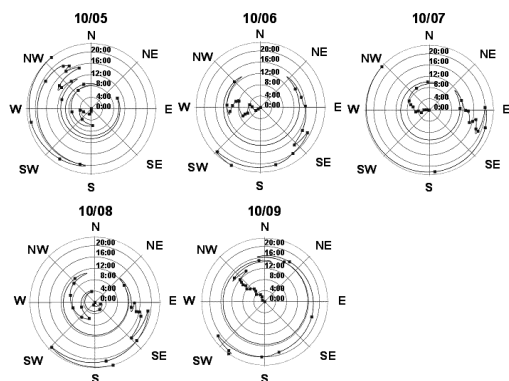


Fig. 6 – Typical daily wind direction polar plots recorded from May to September at the measurement site.

Fig. 6 – *Grafici polari giornalieri della direzione del vento misurati da maggio a settembre nel sito di misura.*

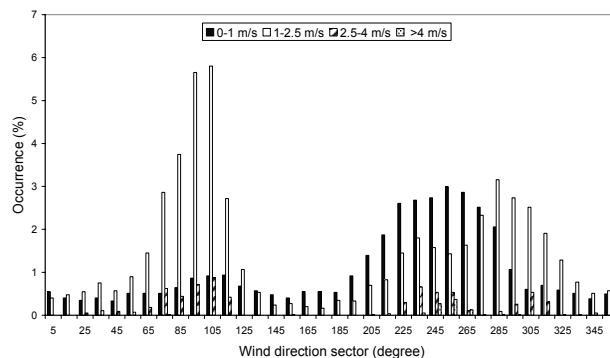


Fig. 7 – Classes of wind speed and occurrence as a function of wind direction.

Fig. 7 – *Classi della velocità del vento in funzione della direzione.*

Meteoclimatic characterization

Fig. 4 and 5 respectively report 2003 temperature monthly values and rainfall amounts. January and February were characterized by negative values of minimum temperatures, with mean temperatures of about 1 °C. During the growing season the mean temperature was 20°C in May, 26°C in June and July, 28°C in August and 18°C in September. The thermal variation reached its maximum of about 16°C in August, when maximum temperature raised values higher as 36 °C. The precipitation trend followed the climatological series typical of the area (Lenzi *et al.*, 1986), but during the summer months a lower amount of rainfall was recorded. May and June were in fact characterized by precipitation values close to zero.

Monthly wind direction data analysis clearly indicates that the site is subject to a well characterized local land-sea breeze circulation system during the growing season (Fortezza *et al.*, 1993). It is worthwhile to notice the rotation of the breeze during the late afternoon in all the summer months (Fig. 6). Such a wind regime generates higher velocities when sea breeze, typical of Adriatic coast, occurs (2.5 - 4 m s⁻¹), and lower for land breeze

conditions (usually below 2.5 m s⁻¹). The wind speed sector distribution recorded in our orchard confirms a local breeze circulation system, being the greatest number of data with higher wind speed (>2.5 m s⁻¹) from the sector NE-SE (sea breeze), and with the lowest wind speed (<2.5m s⁻¹) from the sector NW-SW (land breeze). A remarkable gap in wind occurrence is recorded for the remaining directions (Fig.7). Such a pattern in wind direction, induced by the differential sea-land heating, has a remarkable effect on the local atmospheric stability conditions. Fig. 8 shows the atmospheric stability plotted as a function of wind direction. All the stability conditions are characterized by a bimodal distribution, that appears differently distributed according to the wind sector. The convective conditions correspondent to thermal turbulence reach the maximum occurrence when sea breeze blows along with adiabatic conditions characterizing mechanical turbulence. Both convective and adiabatic secondary maxima correspond to NW wind directions, typical of morning hours. On the other hand, nearly all stable events are distributed in the NW-SW sectors, characteristic of night-time periods.

Flux data quality

Ideal sites from the micrometeorological point of view are extensive continuous canopies on flat terrain. Our orchard was selected on the basis of its extension (18 ha), considerable in extent given the typical land frag-

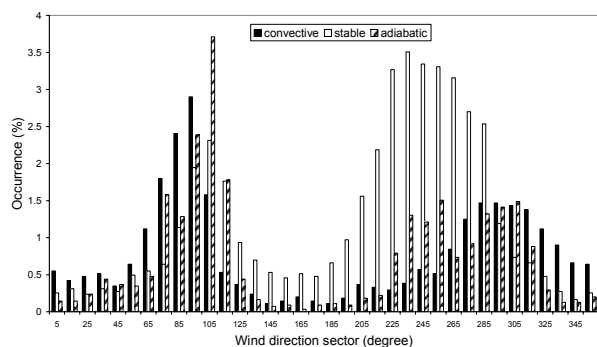


Fig. 8 – Atmospheric stability distribution as a function of the wind direction.

Fig. 8 – Distribuzione della stabilità atmosferica in funzione della direzione del vento.

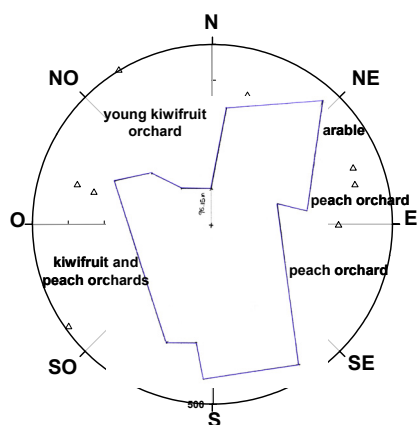


Fig. 9 – Map of the orchard, soil use in the proximities and footprint analysis. Circles indicate the maximum of the total flux and the triangles represent the 80% of the total flux.

Fig. 9 – Mappa del frutteto con uso del suolo dei terreni confinanti, i cerchi indicano da dove proviene il massimo contributo ai flussi totali, i triangoli il contributo dell'80%.

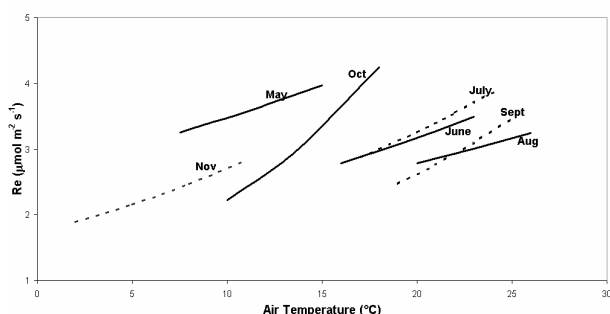


Fig. 10 – Monthly relationship between respiration and air temperature. The curves are the exponential regression fitted by the least squares method of the Lloyd and Taylor (1994) parameterisation.

Fig. 10 – Relazione mensile tra respirazione e temperatura dell'aria. Le curve esprimono la regressione esponenziale mensile secondo la parametrizzazione di Lloyd e Taylor (1994).

mentation of the rural areas in Northern Italy, with the aim to satisfy the fetch requirement imposed as a rule in fluxes monitoring.

A footprint analysis was carried out for a continuative one-month period following the methodology proposed by Schuepp *et al.* (1990). Figure 9 shows the upwind distances most likely to contribute to our measured fluxes for 80% and maximum of the total. Such analysis evidences that the higher part of the relative flux density is well within the orchard surface, making the fetch conditions at our orchard likely to be acceptable.

After despiking, detrending and application of the stationarity tests to the raw data (Aubinet *et al.*, 2000), a quality check was applied to the carbon fluxes, rejecting values out of the range - 50 to 10 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Major errors in calculating fluxes may easily occur during stable atmospheric conditions (Aubinet *et al.*, 2002). To minimize this effect, the storage of CO₂ in the layer below the eddy measurements was computed by integrating the temporal variations of the CO₂ concentration measured at the top of the canopy (Greco and Baldocchi, 1996). To avoid errors due to the low nocturnal turbulence regimes, night data were carefully inspected to detect invalid values (i.e. carbon flux negative values, values out the night trend). We preferred such a methodological procedure instead of the usually adopted correction based on u* threshold established values that, when applied to our measurements, showed a lower performance both in guaranteeing data quality and in maintaining a representative nocturnal data set.

As a consequence of the above described quality checks, 23% of the data were rejected in May, 16% in

Tab. 4 – Coefficients of CO₂ flux and air temperature obtained by applying Lloyd and Taylor (1994) parameterisation for each month.

Tab. 4 – Coefficienti ottenuti applicando per ogni mese la parametrizzazione di Lloyd e Taylor (1994) ai flussi di CO₂ e alla temperatura dell'aria.

| Month | b ₁ | b ₂ | R ² |
|-----------|----------------|----------------|----------------|
| May | 2.67 | 0.026 | 0.90 |
| June | 1.54 | 0.046 | 0.95 |
| July | 1.39 | 0.043 | 0.91 |
| August | 1.67 | 0.026 | 0.95 |
| September | 0.85 | 0.057 | 0.79 |
| October | 0.99 | 0.081 | 0.85 |
| November | 1.73 | 0.045 | 0.94 |

Tab. 5 –Coefficients of CO₂ flux and PAR calculated for kiwifruit according to Dagnelie (1991) parameterisation.

Tab. 5 – Coefficienti ottenuti applicando la parametrizzazione di Dagnelie (1991) ai flussi di CO₂ e alla PAR.

| Month | b ₁ | b ₂ | b ₃ | R ² |
|-----------|----------------|----------------|----------------|----------------|
| May | -17.48 | 0.0028 | -6.39 | 0.56 |
| June | -16.22 | 0.0026 | -4.11 | 0.65 |
| July | -14.26 | 0.0029 | -4.20 | 0.58 |
| August | -12.46 | 0.0026 | -3.05 | 0.60 |
| September | -15.46 | 0.0019 | -0.99 | 0.60 |
| October | -14.25 | 0.0012 | -0.78 | 0.80 |
| November | -13.78 | 0.0018 | -0.27 | 0.65 |

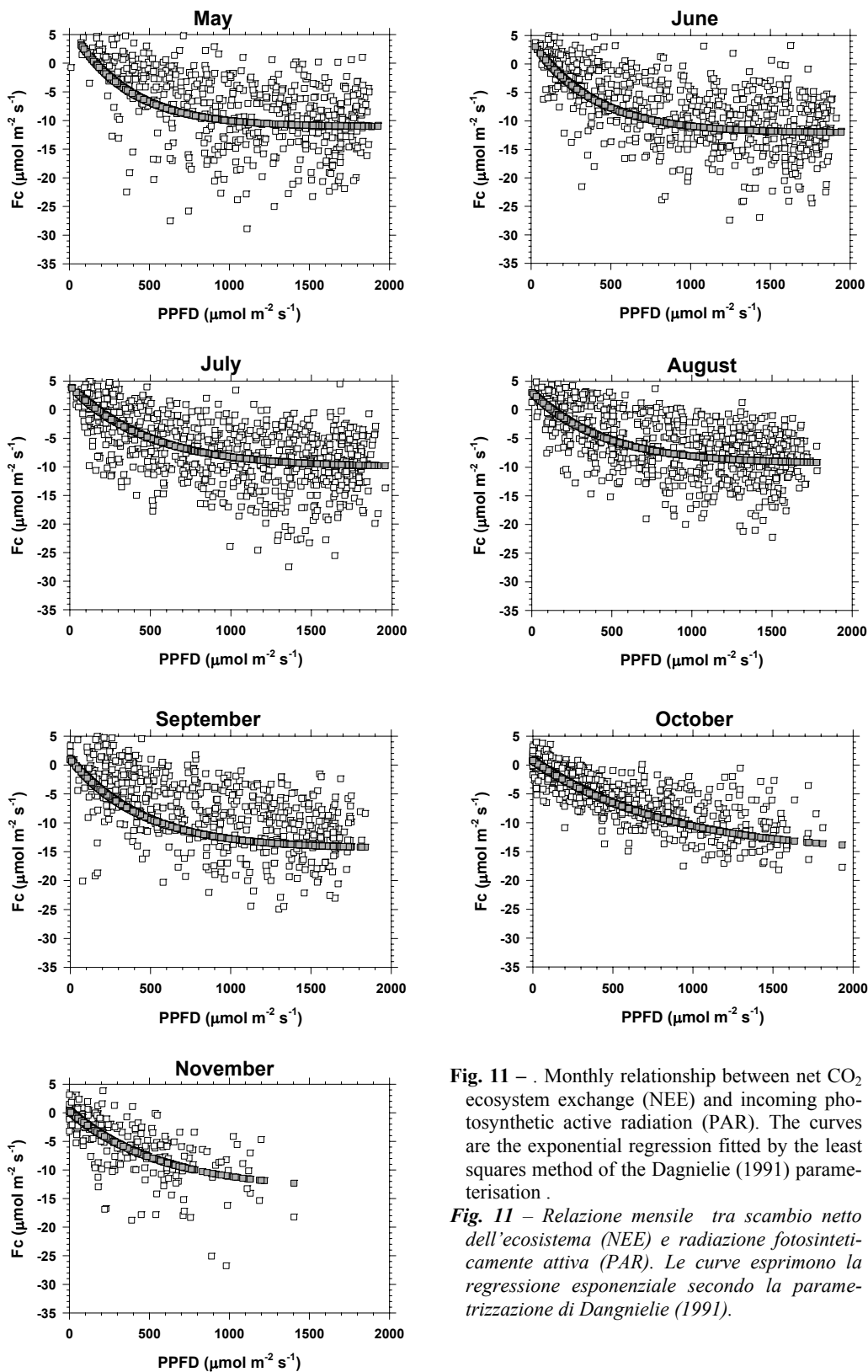


Fig. 11 – Monthly relationship between net CO₂ ecosystem exchange (NEE) and incoming photosynthetic active radiation (PAR). The curves are the exponential regression fitted by the least squares method of the Dagnielie (1991) parameterisation .

Fig. 11 – Relazione mensile tra scambio netto dell'ecosistema (NEE) e radiazione fotosinteticamente attiva (PAR). Le curve esprimono la regressione esponenziale secondo la parametrizzazione di Dagnielie (1991).

June, 2% in July, 11% in August, 17% in September, 8% in October, 30% in November. A procedure of gap-filling has been hence performed to assess the net ecosystem exchange during the entire growing season. When data gaps were lower than three consecutive hours, data have been linearly interpolated. In all the other cases, the procedure suggested by Falge *et al.* (2001) has been followed.

As far as nocturnal fluxes (respiration) are concerned, the nighttime missing data have been reconstructed applying the relation between night fluxes and air temperature (Lloyd and Taylor, 1994):

$$R_e = b_1 e^{b_2 T_{air}}$$

where R_e is the ecosystem respiration, and b_1 and b_2 the coefficients computed for each month (Tab. 4). The monthly temperature response functions evaluated from all the nighttime data are reported in Fig. 10. The nocturnal respiration increases during the growing period until the end of June and slowly decreases during the summer months even in presence of a temperature increase. This trend may be consistent with the seasonal evolution of the bioenergetic costs due to both biomass synthesis and maintenance (Walton and Fowke, 1995). In fact, in kiwi as in deciduous tree crops the carbon requirements for biomass maintenance is very high during canopy development (Buwalda *et al.*, 1991).

The few missing diurnal fluxes have been gap-filled by utilizing the relation between the carbon

flux and the photosynthetic photon flux density (PPFD) proposed by Dagnielie (1991):

$$F_{day} = GPP_{OPT} \left(1 - e^{-\frac{aPPFD}{GPP_{OPT}}} \right) - R_{day}$$

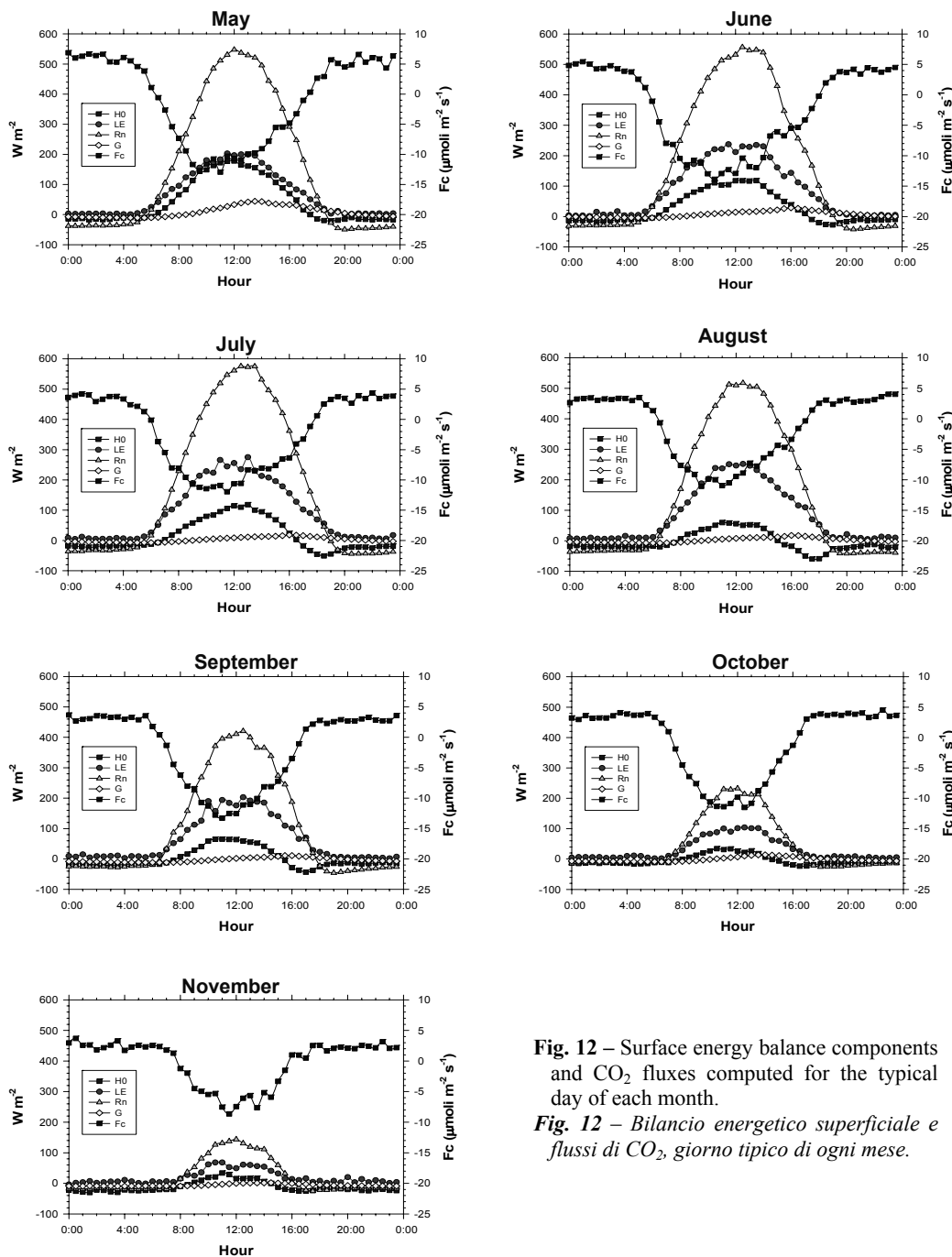


Fig. 12 – Surface energy balance components and CO₂ fluxes computed for the typical day of each month.

Fig. 12 – Bilancio energetico superficiale e flussi di CO₂, giorno tipico di ogni mese.

typical days for each of the seven months of measurements (Fig. 12). The micro-meteorological sign convention in which positive values represent a release from the surface (upward fluxes) and negative values represent an uptake by the surface (downward fluxes) was followed.

The most remarkable amount of energy partitioning throughout the whole season was due to latent heat flux, that had values approximating to those of sensible heat flux (about $200 W m^{-2} s^{-1}$ at midday) only in May, when leafy biomass was still developing. From June to September, latent heat flux kept constantly at about 50% of R_n , and did not appear to be influenced by the air temperature, very high in its maximum values during the three months of June, July, August. Such an evapotranspiration diurnal pattern appears typical of unstressed vines (Gucci *et al.*, 1996), evidencing a rapid rise of stomatal conductance in the early morning with little changes during the day until radiation levels decreased again in the late afternoon. The low wind levels recorded at

where GPP_{OPT} is the gross primary production and R_{day} is the diurnal ecosystem respiration. Also in this case, these last parameters have been computed for each month (Tab. 5). The kiwi canopy dose-response function of photosynthesis to PPFD represented as an asymptotic exponential equation shows that the CO₂ flux saturates around $500-700 \mu mol PPFD m^{-2} s^{-1}$. These irradiance values are in agreement to those reported from Grant and Ryugo (1984) for single kiwifruit leaves (Fig. 11).

Fluxes and energy balance

To allow a seasonal representation, the daily patterns of net radiation and fluxes have been calculated for the

night may have probably prevented the high values of stomatal conductance recorded for this species during advective situations (Judd *et al.*, 1986) and consequently avoided the occurrence of nocturnal water use (Green and Clothier, 1988). Sensible heat flux was constantly lower than latent heat flux to confirm the absence of remarkable heating of the canopy throughout the entire season. These findings are evidently related to the continuous irrigation that avoided the kiwi orchard to experience periods of soil water deficit and stress conditions caused by the high summer temperatures. Starting from October the radiation availability drastically decreased thus reducing the energy partition but maintain-

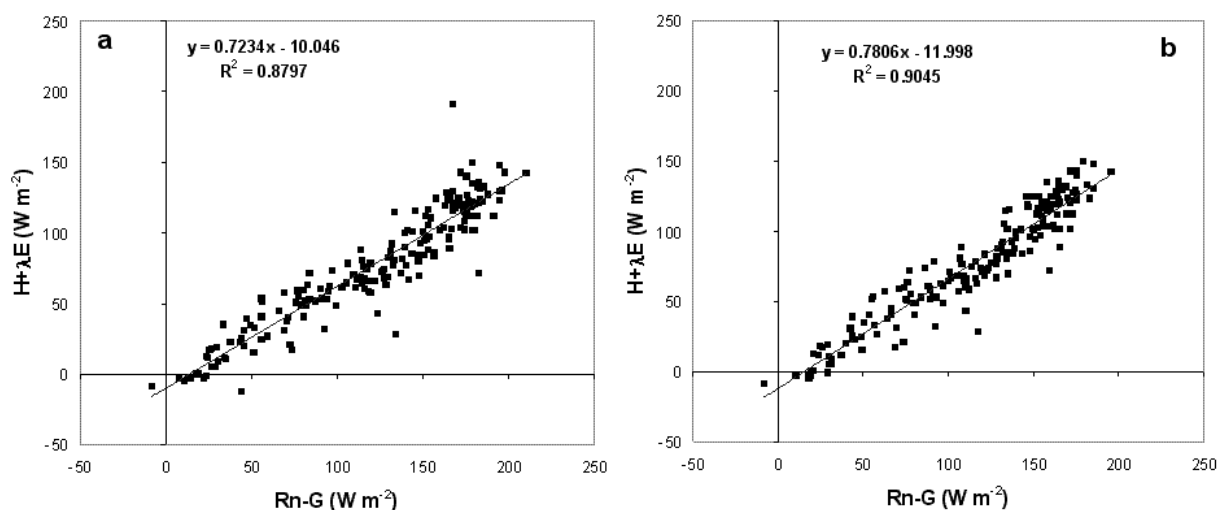


Fig. 13 – . Energy balance closures obtained considering (a) above canopy net radiation and (b) the difference between above and below canopy net radiations

Fig. 13 – Chiusura del bilancio energetico considerando (a) la radiazione netta al di sopra della vegetazione e (b) la differenza tra questa e quella misurata al di sotto della vegetazione.

ing the relative ratio between the turbulent heat flux components.

As evident by the graph in Fig.13a, the energy balance closure obtained by plotting turbulent fluxes against the net radiation measured over the canopy and soil heat flux was less than 28%. An improvement in the surface energy balance closure (Fig. 13b) was obtained by applying the parameterisation proposed by Silberstein *et al.* (2003), which considers the available energy as difference between the over-canopy and below-canopy net radiation. Utilising this correction factor, the slope coefficient of the linear fit increased from 0.72 up to 0.78. Similarly, the correlation coefficient (R^2) was improved, passing from 0.88 to 0.90.

The canopy carbon flux evidenced daylight negative values from the atmosphere to the orchard indicating, as expected, canopy photosynthesis throughout the whole period of measurements.

Canopy carbon assimilation reached maximum values of about $-14 \mu\text{mol m}^{-2} \text{s}^{-1}$ during May and June. Such daily maximums decreased in July and August respectively to -12 and $-10 \mu\text{mol m}^{-2} \text{s}^{-1}$, and turned to $-13 \mu\text{mol m}^{-2} \text{s}^{-1}$ again in September. Going on with the season, a marked decrease of the canopy photosynthesis was observed. The duration of the photosynthetic period was 11 hours in May, 13 hours in June, 12 hours in July, 11 in August, 10 in September, 9 in October and 8 in November. The combination of such two factors (rate and duration) led to the monthly gross primary production values, separately shown in Fig. 14.

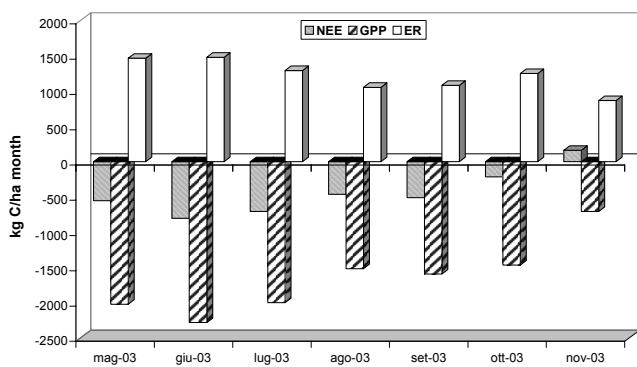
As previously reported by measurement taken at leaf level, a remarkable asymmetry of daily canopy CO_2 assimilation was recorded, in accordance to reports indicating that, at any PAR, canopy kiwifruit photosynthesis is

often lower in the afternoon (Buwalda *et al.*, 1992a, Greaves and Buwalda, 1996). Such a decline in photosynthesis during the day reflects clearly on the cumulated carbon flux when separately integrated for the time of the day.

Fig. 15 shows that an amount between 60% and 75% of the total carbon was fixed from the orchard in the morning between 7 and 12.30. June was the most favourable period for canopy photosynthesis, and daily cumulated carbon flux reached values of $220 \mu\text{mol m}^{-2}$, 65% of them in the morning hours. Total values lowered in the following months, reaching the summer minimum of $127 \mu\text{mol m}^{-2}$ in August, when only 30% of the total photosynthetic flux occurred in the afternoon. The high air temperatures recorded in the summer 2003 may probably have contributed to such a pattern. An increased carbon flux followed in September, when air temperature went to lower maximum values, to confirm the results from Buwalda *et al.* (1991) indicating that maximum photosynthetic capacities are attained in kiwi during 3-5 months after leaf emergency. The carbon assimilation occurring in October and, mainly, after harvest was, of course, strongly limited both by the shortage of radiation and temperature, and by leaf senescence. In November in fact, the net ecosystem exchange (NEE) become positive due to the prevalence of respiration with respect to photosynthesis (Fig. 14).

Observation by bag enclosure methodologies in July also show a daily positive trend, and evidences a temporal correspondence with the onset of photosynthesis recorded by eddy covariance technique (Fig. 16).

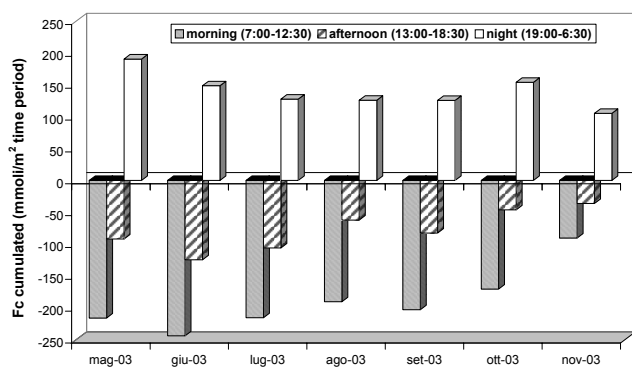
Maximum photosynthetic rates reached about $20 \mu\text{mol m}^{-2} \text{s}^{-1}$. As reported from Succi *et al.* (1994), absolute values for single leaf photosynthesis were higher than



| | mag-03 | giu-03 | lug-03 | ago-03 | set-03 | ott-03 | nov-03 |
|-----|----------|----------|----------|----------|----------|----------|---------|
| NEE | -554.05 | -802.36 | -705.91 | -463.77 | -511.12 | -215.76 | 160.70 |
| GPP | -2020.91 | -2282.27 | -1999.43 | -1517.19 | -1593.63 | -1465.59 | -705.40 |
| ER | 1466.86 | 1479.91 | 1292.00 | 1053.43 | 1082.51 | 1249.83 | 866.10 |

Fig. 14 – Monthly cumulated CO₂ exchange (NEE), gross primary production (GPP) and ecosystem respiration (ER).

Fig. 14 – Scambio netto dell'ecosistema (NEE), produzione primaria lorda (GPP) e respirazione dell'ecosistema (ER) mensili cumulati.



| | mag-03 | giu-03 | lug-03 | ago-03 | set-03 | ott-03 | nov-03 |
|-------------------------|---------|---------|---------|---------|---------|---------|--------|
| morning (7:00-12:30) | -215.94 | -243.93 | -215.60 | -190.34 | -202.98 | -170.55 | -90.29 |
| afternoon (13:00-18:30) | -91.89 | -124.58 | -106.10 | -62.20 | -82.54 | -46.16 | -36.15 |
| night (19:00-6:30) | 190.64 | 148.73 | 127.81 | 125.86 | 125.59 | 154.04 | 105.33 |

Fig. 15 – Canopy carbon flux daily partitioning (morning, afternoon and night hours) during the entire season.

Fig. 15 – Partizione giornaliera dei flussi di carbonio (mattina, pomeriggio e notte) durante l'intera stagione.

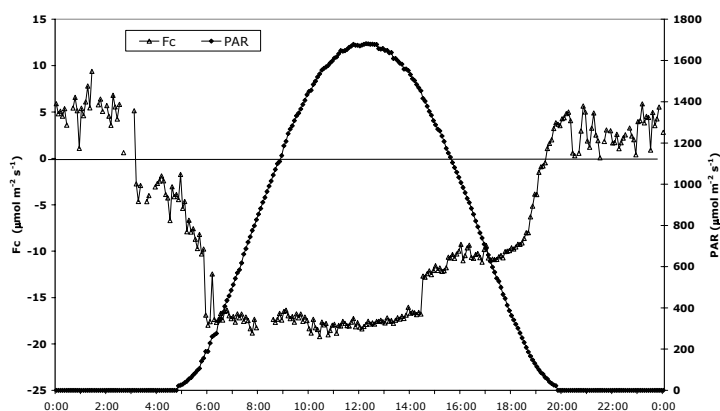


Fig. 16 – Carbon flux during one day of measurement inside a bag enclosure, photosynthetic active radiation (PAR) is also reported.

Fig. 16 – Flussi di CO₂ misurati con la tecnica della "bag enclosure" durante una giornata, viene riportata anche la radiazione fotosinteticamente attiva (PAR).

those observed for whole plants. The diurnal asymmetry in CO₂ fixation was also observed, in accordance to the data reported by Greaves and Buwalda in clear days (1996).

The nocturnal values recorded into the bag confirm at leaf level the respiration pattern evidenced at canopy scale by eddy covariance data.

Water use efficiency

Data from carbon and water fluxes allowed to trace daily and seasonal canopy WUE. Mid-day averaged monthly values indicate that WUE is 0.0027 and 0.0029 in May and June respectively, and decreases to 0.0022 in July up to a minimum of 0.0018 in August. WUE values increase after that time reaching higher values in September (0.0033) and October (0.0046). In each month, the diurnal trend shows constant higher water use efficiencies in the morning hours, evidently matching the photosynthetic daily patterns.

Conclusions

Eddy covariance appears to be a suitable methodology to assess whole-canopy net photosynthesis and its seasonal variation over large extensions orchards, kiwifruit in this case. The direct measurement of carbon exchanges at whole stand level through micrometeorological applications can be greatly helpful since it can overcome some limitations intrinsic to scaling-up models to describe canopy photosynthesis. In the case of kiwifruit, for example, diurnal decline of photosynthesis observed on individual leaves appears difficult to be modelled since its poor correlation with stomatal conductance (Grant and Ryugo, 1984), and kiwifruit leaves are likely to be subjected to patchy stomatal closure, making local measurements on leaves possibly misleading (Terashima, 1992).

Several whole canopy studies have shown a pronounced diurnal patterns manifested as a progressive reduction in the quantum efficiency of photosynthesis, that has been ascribed to the influence of various environmental stresses and endogenous regulatory mechanisms. The same diurnal depression recorded in kiwifruit (Chartzoulakis et al., 1993) has been manifested also by our orchard-scale measurements, that evidence diurnal changes in the efficiency of photosynthesis in all summer months, when reduced photosynthesis rates occurred during the period of peak irradiance and temperature. Apparently, the involvement of non-stomatal limitations can be confirmed in

such afternoon depression in carbon assimilation (Buwalda *et al.*, 1992b), since partial stomatal closure did not appear by the daily patterns of latent heat fluxes under our conditions of non-limiting water supplies.

The eddy data can be hence considered an important direct input information to understand the dynamics of carbon acquisition and utilization in kiwifruit orchard, modelled so far starting by simulated canopy net photosynthesis and respiration (Buwalda, 1991). The ecosystem fluxes reported here were recorded in a orchard system whose biomass values were in very good agreement with those indicated for a similar kiwifruit system grown elsewhere (Buwalda and Smith, 1987), indicating a realistic opportunity of their utilization in specifically developed models.

Due to the awareness of the increasing greenhouse gases concentration, the measurements carried out also had the aim to contribute to the understanding of carbon balance in different vegetation systems to quantify their sink and source activities. At this purpose, the seasonal timing and the amplitude of the net system carbon flux as well as of the components fluxes corresponding to assimilatory and respiratory processes have been quantified. The Net Ecosystem Exchange of the kiwifruit system monitored in this study was at around 3 t of carbon during the seven months leafy period (useful to produce 12.5 t total biomass ha^{-1} , more than 50% partitioned to perennial structures), when 8.5 t of carbon were lost in ecosystem respiration (Fig. 17). Such fluxes are the sum of contribution from both kiwifruit plants and cover crop, present during all the season.

The rule of the kiwifruit orchard to positively act in atmospheric carbon sequestration throughout the whole vegetative and productive season appears evident, with maximums in the spring and early summer, while the beginning of its source activity started in November, in correspondence with the very limited photosynthetic efficiency of senescent leaves and the response to meteorological fall conditions. The data obtained for the orchard studied here can be assumed a valid indication of the contribution to the carbon balance of a kiwifruit orchard grown according to the common agricultural techniques, irrigation included. However, limits to generalizations come from the fact that measurements are indicative of only one-year activity, and refer to 2003, when severe heat wave was recorded, raising summer temperatures 20 to 30% higher than the seasonal average. Although we can take the records taken in 2003 as indicative of the functioning of a kiwifruit in a climate change scenario, more continuous interannual monitoring to detect possible differences arising in different years in relation to meteorological conditions appears very important to reach a generalization.

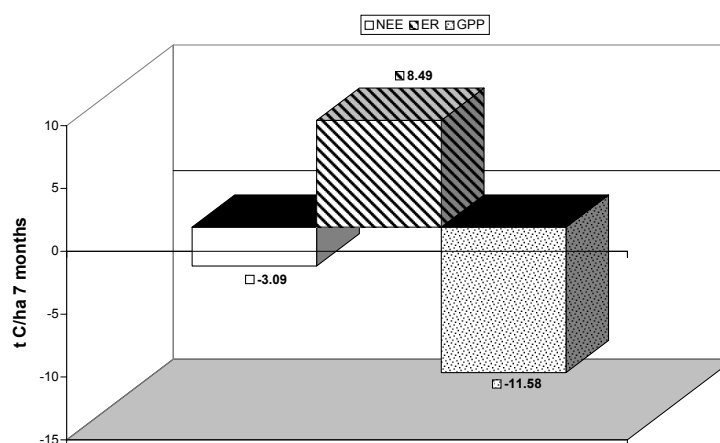


Fig. 17 – CO₂ net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration (ER) cumulated from the beginning of the vegetative season to the leaf abscission .

Fig. 17 – Scambio netto dell'ecosistema (NEE), produzione primaria lorda (GPP) e respirazione dell'ecosistema (ER) cumulate dall'inizio della vegetazione all'abscissione delle foglie.

Kiwifruit variety assortment is very limited and Hayward is still the most popular variety in the Countries growing *Actinidia*. Also, training systems and agronomic practices are very similar (Warrington and Westin, 1990). This homogeneity can help the generalization of carbon dependence also by genetic attitude in respect to other fruit trees species, where cvs, rootstocks, training systems, planting densities, presence or absence of irrigation and, when this is present, different timing and amounts of water given, can be very differentiated and hence possibly exerting major effects.

It has to be remarked also the importance of additional need to separately measure the autotrophic contribution and the heterotrophic respiration and to test the reliability of existing methods to splitting the above/below ground total ecosystem respiration in orchards (Hanson *et al.*, 2000, Mc Dowell *et al.*, 2004). Several very recent information in this field have been made available for a wide range of forest ecotypes also in relation to their species composition, age and location and net uptake estimates can be improved also considering correction methods for advection and for low levels of turbulence (Paw U *et al.*, 2004).

The optimisation of water supply is a urgent need in terms of sustainable fruit tree production and the sensitivity of *Actinidia* fruit growth to water availability has been well documented for harvest weight and quality attributes (Miller *et al.*, 1998; Holzapfel *et al.*, 2000). In addition to the other considerations, carbon flux data continuously assumed at whole orchard level can offer important information in determining time trends of WUE, allowing a more realistic scientific-based irrigation management based on the understanding of crop-atmosphere interactions.

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