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Research Paper

Eddy correlation measurements to visualize CO_2 and water vapor concentrations and fluxes

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ABSTRACT

Eddy correlation also known as eddy measures gas exchange between canopy and the overlying atmosphere by evaluating the correlation between fluctuations in the gas-of-interest's mixing ratio and the vertical wind velocity and considered the most accurate approach for measuring gas fluxes, mostly carbon dioxide and water vapor under ideal homogeneous conditions. It has been used in micrometeorology for decades to quantify mass and energy transfer between urban, natural and agricultural ecosystems and the atmosphere. We assessed its application under various homogeneous and non-homogeneous conditions. Our study indicates that fluxes of CO_2 and H_2O correlate well with plants activity only when turbulent conditions are present, in open fields. At such conditions, direct measurements of concentration of those gases are not an accurate indicator for plants activity. On the other hand, in closed systems (e.g. greenhouses)- fluxes as measured by an eddy correlation system can't accurately be related to the state of the vegetation, but the fluctuations in the concentrations of CO_2 and H_2O directly correlate to the actual plants activity. Adapting conditions in greenhouses to limiting factors as temperature, increases CO_2 sequestration by plants, and may increase productivity

Keywords: Eddy correlation/covariance; CO_2; water vapor; atmospheric gas fluxes; atmospheric gas concentration.

Carbon dioxide (CO_2) concentration in the atmosphere is well-known to be increasing, from mean monthly mixing ratio values of 315 μmol CO_2 per mol air molecules (typically denoted as parts per million [ppm]) in 1958 to 420 ppm in 2022 (Tans and Keeling, 2022). A graphical description of this increase is given by the Keeling Curve, named after Charles David Keeling, who began monitoring CO_2 concentration in Mauna Loa, Hawaii in 1958, developed the methodology and explained the trends. For example, one of his observations was that the concentration was higher at night than during the day. Based on the literature, he attributed this to the fact that during the day, turbulence mixes the air upward, giving nearly constant readings (at that time ~310 ppm CO_2) in all locations, but during the night, cooler air accumulates near the ground, and CO_2 increases due to plant respiration and lack of mixing (Harris, 2010).

The importance of the Keeling Curve in Environmental Science Education has been enormous: "The Mauna Loa curve, simple and unambiguous, thrust itself before humanity's eyes, changing our view of the world. Keeling's work was far ahead of its time" (Nisbet, 2007). It certainly depicts the general trend of the process and changes in the atmosphere. Seasonal fluctuations also illustrate the changes on a timescale of weeks or months, as seen by differences between winter and summer. But can such changes be monitored directly and instantaneously to yield information on the real-time influence of a process, such as photosynthesis, on the CO_2 concentration above plants?

Although it is obvious to biologists and plant physiologists that when a plant performs photosynthesis, it combines water from the soil with CO_2 absorbed from the atmosphere, the measurement of those processes in the atmosphere is complicated and non-intuitive. As stated in the literature (Baldocchi and Meyers, 1998): "Diagnosing and predicting how concentrations of trace gases may vary with time in the atmosphere depends, in part, on the rates that materials flow into and out of the atmospheric reservoir." In this sense, the influence of plant photosynthesis is obvious. Although the process of photosynthesis is sometimes written as (Bassham and Lambers, 2022):

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

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this equation does not include the release of water to the atmosphere, and a more correct notation, which emphasizes this release, is (Bassham and Lambers, 2022):

$$6CO_{2(g)} + 12H_2O_{(g)} \rightarrow C_6H_{12}O_6 + 6H_2O_{(g)} + 6O_{2(g)} \quad (2)$$

Equations (1) and (2) described the process known as "gross" or "true" photosynthesis, and it happens only during the day. "Net" photosynthesis, on the other hand, is true photosynthesis minus photorespiration and dark respiration (Wohlfahrt and Gu, 2015), with the latter process being described by Equation (2) written from right to left. Thus, the general picture is that plant activity during the day (or active "true" photosynthesis) removes CO_2 and adds water vapor. However, as Keeling noted, CO_2 concentration during the day in an open field appears to remain constant. To visualize those effects, we use eddy correlation (EC) (also called eddy covariance) system measurements to discuss specific points of interest. Full datasets of the different cases presented in the present study (open, closed and mechanically controlled greenhouses and an open agricultural orchard) are supplied as Supplemental Material and might be used by researchers and educators to present these types of relationships.

Eddy covariance/correlation method

Eddy covariance (EC) is a micrometeorological technique used to measure the transport of gases, heat, and momentum across the interface between a surface and the overlying atmosphere (Burba et al., 2013), by measuring covariance between fluctuations in vertical wind velocity and the parameter of interest, for example, CO2 mixing ratio or concentration. The method has "the advantages of elegance and a sound theoretical basis, but it requires fast-response sensors and rapid data acquisition" (Monteith and Unsworth, 2013), and it is considered the main contemporary technique for direct flux measurements on an ecosystem scale (Burba, 2021). It has been widely used since the early 1990s; it has been applied directly over fresh (Assouline and Mahrer, 1993) or hypersaline (Metzger et al., 2018) lake surfaces, and also successfully implemented to quantify irrigation for several field crops, including cotton (Mahrer and Rytwo, 1991), soybean (Otero et al., 2015) and bahiagrass (Jia et al., 2009). It was also applied to quantify evapotranspiration in tress, e.g as in apple orchards (Odi-Lara et al., 2016), olives (Er-Raki et al., 2009) and forest (Mizutani, 1997) trees.

A qualitatively visualization of the principles of the method is presented by Burba et al.. (2013), and explains the process in detail. In general, if we may describe the atmosphere as a series of air parcels moving randomly in all directions. Each parcel has its specific properties (velocity vector on three axes, gas contents, temperature, density). By measuring the properties of each parcel and summing them up (integrating them) for a certain time step, while taking into consideration the velocity vector of each parcel, we may be able to evaluate changes in the parameters, thus: fluxes. Indeed, the method may monitor "carbon and water vapor flux of ecosystem on a direct, precise, and continuous basis and proves itself to be the most efficient method that reveals the interactions between terrestrial biosphere and atmosphere on an ecological scale" (Liang and Wang, 2020).

Several important assumptions are made in the EC method. The first two are: (i) the air- density fluctuations over flat and vast spaces can be safely assumed to be negligible, (ii) the mean vertical flow over a horizontal homogeneous terrain is considered to be negligible as well, so there are no flow diversions or conversions (Burba and Anderson, 2010). Under those two assumptions, fluxes can be mathematically represented as:

$$F \approx \overline{\rho_a}\,\overline{w' x_s{}'} \quad (3)$$

where the flux (F) is equal to the product of mean air density ($\overline{\rho_a}$ kg m−3), and the mean covariance between instantaneous deviations in vertical wind speed (w' in m s-1) and the "mixing ratio" or the gas mole fraction *(x_s'* in mol_s mol^{-1}). This equation is the classical formula for the eddy flux of any gas of interest, and is a simplification of the general basic derivation (Burba et al., 2013). A more detailed mathematical analysis can be found in the literature (Gu *et al.,* 2012).

The EC method emerged for micrometeorology and agriculture. However, considering the hundreds of EC stations that are operational, and the availability of instrumentation that allows accurate, easy and rapid analysis of the data, the method can also be valuable for geological carbon capture, utilization and storage (CCUS) (Burba et al., 2013). From the carbon-balance point of view, EC has contributed to an understanding of how whole ecosystems behave due to changes in environmental factors and has "radically altered how we study and measure the breathing of the terrestrial biosphere in a changing world" (Baldocchi, 2020); it allows us to quantify how the biosphere's metabolism is changing, and enables us to follow trends and metabolic fluxes, and to monitor "how whole ecosystems are responding to multifaceted changes in CO2, temperature, water, and management" (Baldocchi, 2020).

Here, we use EC data from different scenarios, not always under conditions that are optimal or even correspond with the assumptions made for the method, mostly to focus on the difference between "fluxes" and "concentrations" of CO2 and water vapor in the atmosphere.

MATERIALS AND METHODS

Experimental setup

EC measurements were performed using a LI-COR eddy covariance system based on a LI7500 DS open path CO_2 and H_2O analyzer (LI-COR Inc., Lincoln, NE) and a Windmaster PRO Gill Sonic Anemometer (Gill Instruments Ltd., Lymington, UK) connected to SmartFlux® 3 system datalogging; the measurements were processed with internal EddyPro 6.2.2 software running in "Express mode". Global radiation and outside temperature were taken from the Northern R&D agrometeorological web network (http://www.mop-zafon.net/) which has been supplying meteorological data to farmers in northern Israel for more than 30 years.

The EC system was placed in March 2020 and in September 2021 to March 2022 in a lychee tree greenhouse used for agricultural research performed by Prof. Raphael Stern from

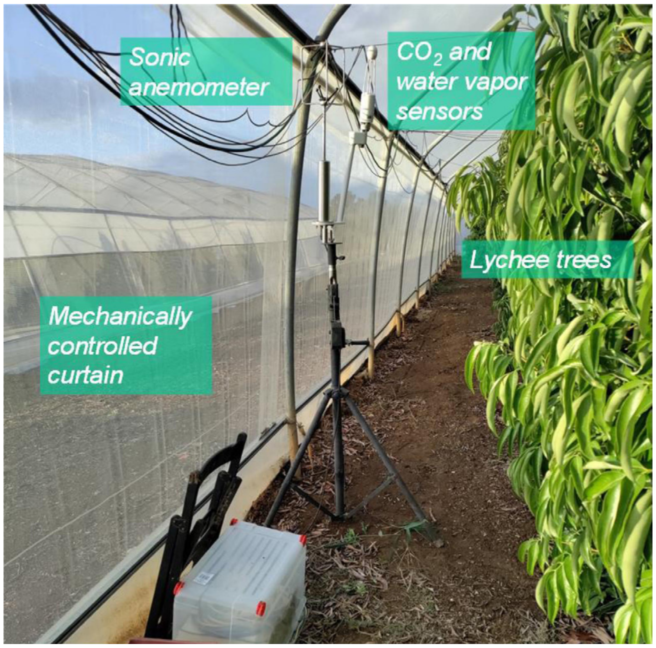

Fig. 1: Lychee trees greenhouse and the measuring instruments tower shown aside from the plants for clarity (photo kindly provided by Mr. Barak Chen).

MIGAL Northern R&D, located in the Hula Valley in northern Israel (33.1528N, 35.6228E, 69 m a.s.l.), at the top of the canopy (3.3 m) (Fig. 1). Global radiation and air temperature data during those periods were taken from the Cabul agrometeorological station, about 3.8 km from the greenhouse (33.1170N, 35.6134E, 66 m a.s.l.).

Since April 2022, the instruments have been installed in an open nectarine orchard in Kibbutz Yiftah, located in the Naftali Hills in northern Israel (33.1260N, 35.5494E, 410 m a.s.l.). Global radiation and air temperature data during this period were taken from the Kadesh Valley agrometeorological station, about 1.1 km from the orchard site (33.1193N, 35.5393E, 395 m a.s.l.).

Four 3-day “scenarios” will be presented:

a. Closed greenhouse, lychee trees during March 2020

b. Open greenhouse, lychee trees during December 2021

c. Closed greenhouse with automated mechanical curtains, lychee trees during January 2022

d. Open field, nectarine orchard during August 2022

RESULTS AND DISCUSSION

Scenario a: closed greenhouse, lychee trees, March 2020

During February and early March 2020, the EC system was installed in a closed plastic greenhouse, with over 2.5 m tall lychee trees, irrigated with geothermal water. Recent studies (Elimelech, 2022; Stern, 2018) have shown that heating lychee trees immediately after the accumulation of “chilling hours” accelerates growth of their blossoms and results in early blooming and fruits that ripen in early May, about 1.5 months before regular commercial orchards.

It is obvious that the assumptions for flux calculations using an EC system are not valid in such a closed and limited environment. However, the instruments measure parameters that might be used without any calculations, such as CO_2 and water vapor mixing ratio/concentration, air temperature, air pressure, humidity, etc. Thus, those parameters represent the real micrometeorological conditions in the greenhouse. Fig. 2 concentrates on 3 consecutive days during that period. Fig.2 shows fluxes that are low, and both CO_2 and H_2O fluxes exhibit strong positive and negative fluctuations that do not seem to be coherent. Although a general trend can be observed in the water vapor flux (positive flux -away from the plants with considerable fluctuations during the day and flux close to zero at night), those results cannot be considered accurate due to the lack of fulfillment of the EC calculation assumptions. However, Fig. 2b shows the results of direct measurements inside (temperature, and CO_2 and water vapor mole fractions) and outside (temperature and global radiation) the greenhouse.

On March 1, the outside temperature ranged from 7–15^{o}C; global radiation increased during the morning to ~250 W m^{-2} but in the early afternoon, cloudiness increased and global radiation decreased to ~150 W m^{-2}. The temperature inside the greenhouse followed the general pattern of the radiation, reaching close to 30^{o}C in the late morning, but when the cloudiness increased, the greenhouse cooled down by 10^{o}C in less than 90 min. As the global radiation increased again, the temperature rose to 31^{o}C in about 1 h (at 1530 h), and then steeply decreased when evening approached. A similar trend can be observed on March 2. On March 3, there was no cloudiness or daytime reduction in global radiation, so the inside temperature reached values of >30^{o}C, and remained high, even after sundown (1700 h).

A very interesting correlation can be seen between the greenhouse temperature and the H_2O mole fraction. At first sight, it can be assumed that this indicates constant relative humidity, since saturation water vapor pressure increases with temperature, but a detailed analysis shows that the relative humidity decreased during the high-temperature periods. The H_2O mixing ratio and temperature correlated with a very good fit along the entire 3-day period (correlation = +0.910). Indeed, many researchers have reported a good correlation between ecosystem respiration and temperature (Liang and Wang, 2020) as the principal component of terrestrial ecosystem, plays an important role in sustaining global substance and energy cycle, adjusting carbon balance and alleviating the rise of atmospheric CO2 concentration and global climate change. Vegetation production of terrestrial ecosystem in particular relates to the process where atmospheric CO2 is absorbed by plants through photosynthesis and dry matter is accumulated by transforming solar energy to chemical energy. Vegetation production, as a major ecological index to estimate sustainable development of ecosystem, reflects the productivity of terrestrial ecosystem under natural conditions. Vegetation covers over 90% of total terrestrial area and its response to global change is very important in that the adjustment to climate change and the mitigation of the rise of atmospheric CO2 level mainly depend on vegetation’s adjustment and feedback

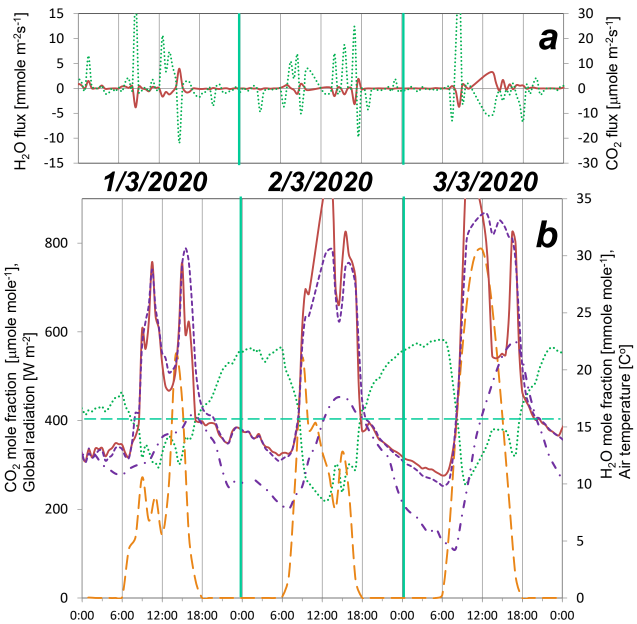

Fig. 2: Measurements in a closed greenhouse with lychee trees during March 2020. (a) H_2O (solid line) and CO_2 (dotted line) fluxes. (b) Interior (dashed) and outside (dash-dot) temperatures, H_2O (solid line) and CO_2 (dotted line) mole fractions, and global radiation (long dashes). Horizontal dashed line in panel (b) indicates regional average CO_2 mole fraction of 405 mmol CO_2 mol^{-1}.

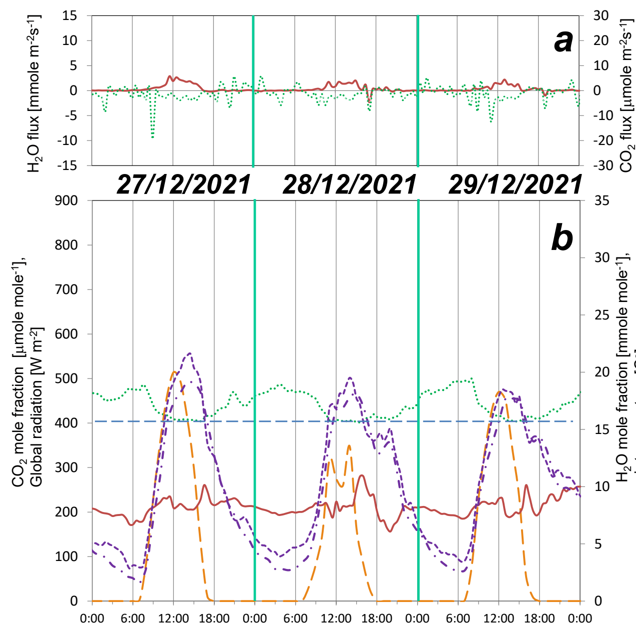

Fig. 3: Measurements in an open greenhouse with lychee trees during December 2021. (a) H_2O (solid line) and CO_2 (dotted line) fluxes. (b) Interior (dashed) and outside (dash-dot) temperatures, H_2O (solid line) and CO_2 (dotted line) mole fractions, and global radiation (long dashes). Horizontal dashed line in panel (b) indicates average CO_2 mole fraction of 405 mmol CO_2 mol^{-1}.

to climate change. Furthermore, about 40% of productivity of terrestrial ecosystem is utilized either indirectly or directly (Vitousek et al., 1997). The only period of misfit was on March 3 at around noon, when the temperature remained high, but the H_2O mole fraction decreased from >35 to ~20 mmol mol^{-1}. This decrease was accompanied by a clear increase in the CO_2 mixing ratio. This combination of effects is generally ascribed to stomatal closing caused by heat stress caused by the high temperatures. Even when considering the short period of closed stomata due to heat stress, a negative correlation between water vapor and CO_2 mole fraction was obvious during the entire 3-day period (correlation = -0.846), very clearly exhibiting the relationship expressed in Equation (2): when no "true" photosynthesis occurs, CO_2 increases and H_2O decreases, and vice versa during the day with open stomata. As mentioned above and seen in Figure 2a, the behavior of the H_2O and CO_2 fluxes in a closed greenhouse appeared random and chaotic, but calculated correlation still yielded a relatively high negative value (-0.801).

To summarize, in the closed greenhouse, even though it is not hermetically sealed, the diffusion from "outside" to "inside" is relatively slow, and during high photosynthetic activity, the CO_2 mixing ratio decreases to values that are almost half of the known average value of about 400 mmol mol air^{-1}, approaching values of ~200 mmol CO_2 mol air^{-1}, close to those considered the lowest threshold for active photosynthesis (Moore, 2015; Moss, 1962). We could not find such low values anywhere in the literature. To ensure that these values were not due to a malfunction in the equipment, they were confirmed with a Rotronic CP11 handheld CO_2, humidity and temperature measuring instrument. On the other hand, during the night, CO_2 reaches values >600 mmol mol^{-1}. A similar but opposite behavior is observed for H_2O mixing ratio: values go down to ~10 mmol mol^{-1} at night or when the stomata are closed and increase to >35 mmol mol^{-1} during periods of high "true" photosynthesis.

Scenario b: open greenhouse, lychee trees, December 2021

On 12 March 2020, a strong easterly windstorm with gusts >100 km h^{-1} partly destroyed the greenhouse roof. The greenhouse was reconstructed, and an improved automatic system that opens or closes curtains depending on the temperature was introduced. Scenario b (Fig. 3) shows measurements performed on 27–29 December 2021—before the automatic system was operational; the side curtains of the greenhouse were constantly open (day and night), and the only coverage was from the roof.

Considering that the main assumptions for the calculation of fluxes using an EC system were again not valid due to the roof that hinders vertical turbulence and other greenhouses in the surrounding area, the fluxes in Fig. 3a showed strong fluctuations; nevertheless the general trend observed in March 2020 (Fig. 2a), where water vapor flux is positive during the day and close to zero at night, was maintained. However, the correlation with CO_2 flux was very low (-0.136).

Fig. 3b shows the direct measurements, which differ considerably from the measurements in March 2020. Outside

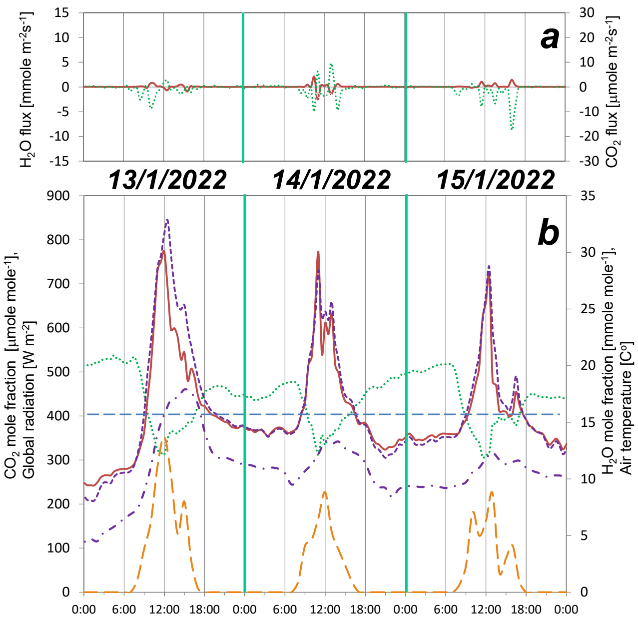

Fig. 4: Measurements in a greenhouse with automatically controlled curtains and lychee trees during January 2022. (a) H_2O (solid line) and CO_2 (dotted line) fluxes. (b) Interior (dashed) and outside (dash-dot) temperatures, H_2O (solid line) and CO_2 (dotted line) mole fractions, and global radiation (long dashes). Horizontal dashed line in panel (b) indicates average CO_2 mole fraction of 405 mmol CO_2 mol^{-1}.

temperatures ranged between 2.8 and 21.6°C. Inside temperatures, which in Fig. 2 differed considerably from the outside values, follow them almost completely in Fig. 3. This can be ascribed to the fact that the greenhouse was completely open to the outside environment. Global radiation increased during the morning, and some noon cloudiness was observed on December 28 with no significant influence on the temperature. The direct and strong correlation between the greenhouse temperature and the H_2O mole fraction observed in Fig. 2b was not apparent here (correlation = +0.381), and we ascribe this to the open sides that allow rapid gas exchange between the interior of the greenhouse and the outside. Similarly, the steep decrease in CO_2 mixing ratio observed in the closed greenhouse was not observed here, and the negative correlation between water vapor and CO_2 mole fractions was not very significant (-0.394). Thus, photosynthesis cannot be monitored under these conditions by neither fluxes nor concentrations.

Scenario c: closed greenhouse with automated mechanical curtains, lychee trees, January 2022

The automatic system was adjusted to open the curtains during the day when the temperature inside increases above 30°C, and close them when it decreases below 26°C. During the winter at night, to avoid high heat stress on the trees, the curtains are left open if the temperature increases above 20°C (Menashe Levy, personal communication, 2022). Scenario c (Fig. 4) shows measurements performed in the greenhouse on 13–15 January 2022, with the automatic curtain system fully operational.

As in the previous scenarios, the main assumptions for EC calculation of fluxes were not valid. Indeed, the fluxes shown in Fig. 4a seem to show "random" fluctuations, as in the previous scenarios. Interestingly, unlike the open greenhouse scenario, the negative correlation between both fluxes was relatively high (-0.830) and similar to the value observed in scenario a (closed greenhouse); thus, as CO_2 flux decreases, H_2O flux increases, and vice versa.

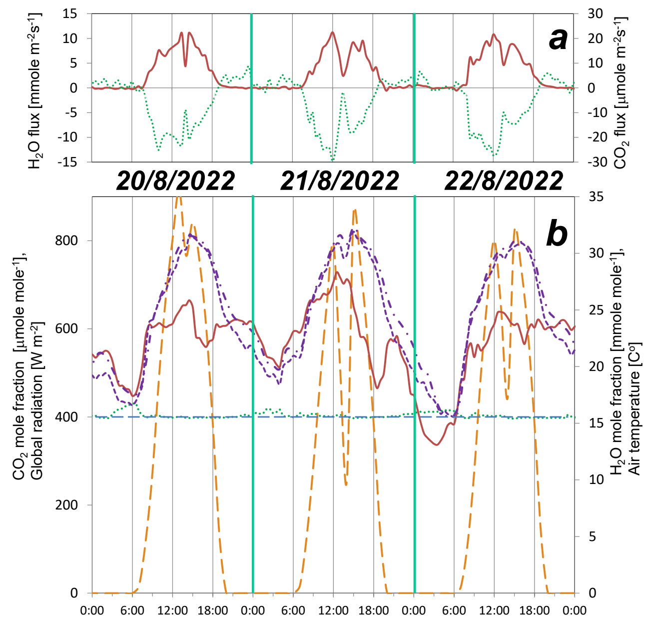

Fig. 5: Measurements in a nectarine orchard during August 2022. (a) H_2O (solid line) and CO_2 (dotted line) fluxes. (b) Orchard (dashed) and meteorological station (dash-dot) temperatures, H_2O (solid line) and CO_2 (dotted line) mole fractions, and global radiation (long dashes).

Fig. 4b differs from the open greenhouse (Fig. 3b) and is relatively similar to the trends for the closed greenhouse (Fig. 2b). During this period, there was a relatively warm winter days, and outside temperatures ranged between 12 and 29°C. During the entire period, global radiation increased during the morning but was influenced by some cloudiness. The inside temperature, similar to Fig. 2b, differed considerably from the outside values, and from Fig. 3b. However, an interesting effect could be observed, ascribed to the mechanical curtains' action: while, for example, on 3 March 2020 (Fig. 2b), the inside temperatures increased to values above 30°C and remained high for several hours, the "cooling" effect of the open curtains can be clearly observed at noon on all 3 days during January 2022: above a certain temperature, a sudden decrease in this parameter is observed, accompanied by an increase in CO_2 and decrease in H_2O. Furthermore, we note that on January 15, the inside temperatures increased again in the late afternoon (1630 h) after steeply decreasing at noon, due to decrease in solar radiation and completely unrelated to the temperature outside. We can explain this as follows: at noon, the temperature reached the higher limit, the curtains opened, and cooler air cooled the greenhouse. In the late afternoon (but still daylight), temperatures reached the lower limit, the curtains closed, and the greenhouse heated up again. This entire effect can also be clearly observed in the fluctuations of H_2O and CO_2 mixing ratios.

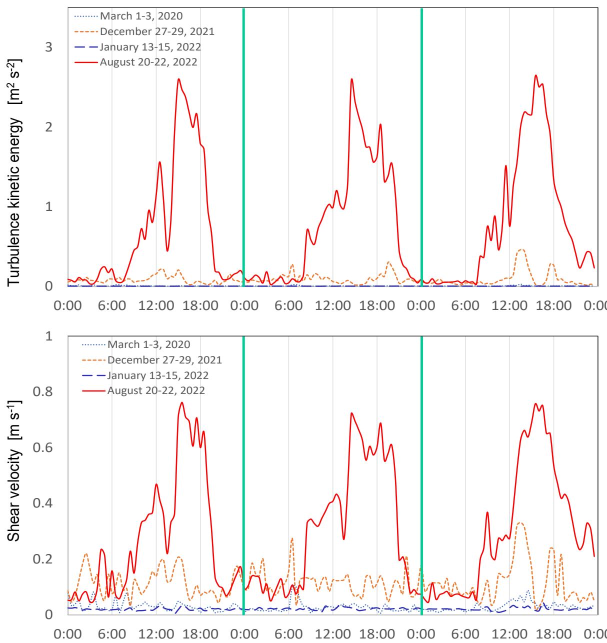

Fig. 6 : Shear velocity (u^*) and turbulence kinetic energy (TKE) for the four 3-day scenarios: (a) closed greenhouse (March 2020, dotted line), (b) open greenhouse (December 2021, dashed line), (c) closed greenhouse with automated curtains (January 2022, long dashed line) and (d) open field orchard (August 2022, solid line).

The direct and strong correlation between greenhouse temperature and H_2O mole fraction seen in the closed greenhouse was also observed in this scenario, and even enhanced (correlation = +0.980; Fig. 4b). The higher correlation (compared with scenario a) might prove the efficiency of the curtain mechanism in avoiding periods of high temperature stress as with the misfit observed in Fig. 2b on March 3, although some stomatal closing still seemed to occur at noon, as indicated by a decrease in H_2O accompanied by a slight increase in CO_2 mixing ratio. The negative correlation between water vapor and CO_2 mole fractions is again obvious during the entire 3-day period, with values similar to those observed in Fig.2b for the closed greenhouse (correlation = -0.843), and considerably higher than those measured in the open greenhouse (Fig. 3b).

CO_2 mixing ratio gives interesting information on the "closure" of the greenhouse. At night, with the curtains closed, values increase to over 500 mmol mol^{-1}. As the solar radiation increases and photosynthesis begins, when temperatures are still low and the curtains are still closed, the CO_2 mixing ratio decreases, reaching values of ~300 mmol mol^{-1}. At noon, the temperature increases and the curtains open, air with more CO_2 enters the greenhouse, its mixing ratio increases and, in some cases (see January 15 at 1530 h), even reaches the mean regional value of ~400 mmol mol air^{-1}. In cases where the curtains close again due to colder temperatures, mixing with the outside stops, and photosynthesis causes another decrease in the CO_2 mole ratio (see January 15 at 1600–1630 h). Thus, in the closed but automatically controlled greenhouse, diffusion from the "outside" to the "inside" depends strongly on the curtain position.

Scenario d: open field, nectarine orchard, August 2022

The last scenario to be discussed is an outdoor orchard during the summer. During the spring and summer of 2022, the instruments were installed in an open nectarine orchard located in northern Israel, 410 m a.s.l. Fig. 5 shows measurements performed in the orchard on 20–22 August 2022.

Unlike the previous scenarios, here the assumptions for the EC calculation of fluxes were valid: the field is large enough and relatively homogeneous. Accordingly, fluxes shown in Fig. 4a appear to be significant, and the pattern emerging from the measurements is clear: during the day, CO_2 flux is negative (toward the plants) and H_2O flux is positive (evaporation from the plants). At night, water vapor flux is close to zero, while CO_2 flux exhibits relatively low positive values due to respiration.

The negative correlation between both fluxes was relatively impressive (-0.936). It is interesting to note some specific moments along the graph. For example, for all 3 days at noon, cloudiness formed and there was a reduction in global radiation (Fig. 5b). This is particularly salient on August 21, when even a few millimeters of rain were measured in some nearby regions. Immediately after the cloudiness appeared, CO_2 flux increased (became less negative) and H_2O flux decreased (Fig. 5a). When the clouds vanished, the former fluxes were restored. No such clear effect was noticed in scenarios a–c.

As for the temperatures, since it is an open field, we did not expect to see differences between the orchard and the meteorological station nearby (Fig. 5b). It is interesting to note that there was some correlation between temperature and water vapor mixing ratio (0.709), but it was considerably lower than that observed in the closed greenhouse. On the other hand, CO_2 mixing ratio remained almost constant during the day, with a slight increase at night when the air was stagnant, as noticed decades ago by Keeling (Harris, 2010), and mentioned in the introduction.

Fluxes or concentrations?

As we can see from the different scenarios, when trying to deduce photosynthetic activity, there is no single parameter that can give an accurate indication. In some cases (scenarios a and c, closed or mostly closed greenhouse), the changes in the "total amount" or "concentration" of the gas described by its mixing ratio/molar ratio can yield important information on the gross photosynthesis. In completely open systems (scenario d), "concentration" does not deliver accurate information due to turbulence and rapid gas exchange, but in those cases, the fluxes (Fig. 5a) accurately describe the plant activity. In partially open systems (open greenhouse, scenario b), neither fluxes nor concentrations "work": the fluxes are inaccurate due to the roof that hinders turbulence, and the concentrations fail to describe the process, because the open sides allow relatively rapid gas mixing between the inside and outside.

In looking for parameters that might give an indication of which measurement will be appropriate, we assume that they should be related to turbulence. Turbulence properties are described by the Monin–Obukhov similarity theory (MOST), which provides a set of equations that relate turbulence to atmospheric parameters (Moorhead, 2018). A key parameter in MOST is the friction or shear velocity (u*), which relates shear stress to air density, and gives information on the vertical transport of momentum, or turbulence generation (Camuffo, 2014). Other relevant parameters associated with eddies in turbulent flow are the turbulence kinetic energy (TKE), defined as the mean kinetic energy per unit mass, the dimensionless stability parameter that is derived from the height of the measurement, and several parameters included in the "Obukhov length" (among them u*, temperature, kinematic heat flux, air density and heat capacity). EddyPro software evaluated all of these parameters based on the EC system described in the materials and methods section.

Fig. 6 shows u^* and TKE evaluations for scenarios a–d, offering a perspective on the conditions required to decide which parameter to use: when turbulence is hindered by the greenhouse roof and side curtains (scenarios a and c), both u^* and TKE are almost zero. On the other hand, when turbulence reigns (scenario d, open field orchard), both values are almost zero during the night, but reach large values during the day. Scenario b has open sides, but also upper coverage. Some turbulence is indeed observed, as reflected by low but noticeable values of both u^* and TKE. The measured values during almost the entire 3-day period are 10–20% of the shear velocity and 1–5% of the TKE in the open field. Results for the stability index (not shown in the figure, due to the chaotic fluctuations of the values) also yield similar information: since values of this parameter might be positive or negative depending on the conditions, the regular average value is meaningless. However, the root mean square of the stability index yielded, for scenarios a–d, dimensionless values of 78.9, 1.31, 51.5 and 0.581, respectively. As with the other turbulence-related parameters, lack of turbulence (large values of stability index) are observed for scenarios a and c. The strongest instability (lowest stability index) occurs in scenario d, whereas scenario b exhibits low stability, but still higher than in the open field.

CONCLUSIONS

When turbulence as measured by shear velocity, TKE or stability index is considerable (as in scenario d), CO_2 and water vapor fluxes yield direct information on photosynthetic activity. When turbulence is hindered, either partially (scenario b) or almost completely (scenarios a, c), the fluxes cannot deliver any information on photosynthesis. However, where turbulence and diffusion from the surrounding are almost completely avoided (closed greenhouse, scenarios a, c), information about plant activity can be accurately obtained from changes and fluctuations in gas (H_2O and CO_2) mixing ratios or concentrations.

Measurements confirm the advantage of regular agricultural practices in greenhouses, as avoiding high temperatures for long periods by opening side curtains during the warm hours winter: indeed, scenario c and additional not-shown measurements during that period demonstrate that such activities avoid heat stress to the plants.

As described by Baldocchi (2020), eddy correlation measurements allows us “to find surprises and discoveries by serendipity, which has its own intrinsic merit.” The method yields a huge amount of measured micrometeorological information that might help us (students, educators, and scientists) better understand the behavior of the biosphere as it is influenced by atmospheric conditions. The differences between fluxes and concentrations, and their clear relationship to turbulence, is not obvious, and should be taken in consideration when analyzing plants behavior.

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REFERENCES

Assouline, S., and Mahrer, Y. (1993). Evaporation from Lake Kinneret: 1. Eddy correlation system measurements and energy budget estimates. Water Resour. Res., 29(4): 901–910. https://doi.org/10.1029/92WR02432

Baldocchi, D., and Meyers, T. (1998). On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: a perspective. Agric. For. Meteorol., 90(1–2): 1–25. https://doi.org/10.1016/S0168-1923(97)00072-5

Baldocchi, D. D. (2020). How eddy covariance flux measurements have contributed to our understanding of Global Change Biology. Glob. Chang. Biol., 26(1): 242–260. https://doi.org/10.1111/gcb.14807

Bassham, J. A., and Lambers, H. (2022). Photosynthesis | Definition, Formula, Process, Diagram, Reactants, Products, &

Facts | Britannica. Encyclopedia Britannica. https://www.britannica.com/science/photosynthesis

Burba, G., and Anderson, D. (2010). A brief practical guide to eddy covariance flux measurements: principles and workflow examples for scientific and industrial applications (LI-COR Biosciences (ed.)). LI-COR Biosciences.

Burba, G., Madsen, R., and Feese, K. (2013). Eddy Covariance Method for CO_2 Emission Measurements in CCUS Applications: Principles, Instrumentation and Software. Energy Procedia, 40: 329–336. https://doi.org/10.1016/J.EGYPRO.2013.08.038

Burba, G. (2021). Atmospheric flux measurements. In M. W. S. Weidong Chen, Dean S. Venables (Ed.), Advances in Spectroscopic Monitoring of the Atmosphere (pp. 443–520). Elsevier. https://doi.org/10.1016/B978-0-12-815014-6.00004-X

Camuffo, D. (2014). Atmospheric Stability and Pollutant Dispersion. In Dario Camuffo (Ed.), Microclimate for Cultural Heritage (2nd ed., pp. 245–282). Elsevier. https://doi.org/10.1016/B978-0-444-63296-8.00008-1

Elimelech, D. (2022). Not just a spa from nature: the surprising use of the "hot geysers" in the north. The Limited Times & Walla News. https://newsrnd.com/life/2022-02-20-not-just-a-spa-from-nature--the-surprising-use-of-the-%22hot-geysers%22-in-the-north---walla!-tourism.Bk8oQNgg9.html

Er-Raki, S., Chehbouni, A., Ezzahar, J., Khabba, S., Boulet, G., Hanich, L., and Williams, D. (2009). Evapotranspiration partitioning from sap flow and eddy covariance techniqu es for olive orchards in semi-arid region. Acta Hortic., 846: 201–208. https://doi.org/10.17660/AsctaHortic.2009.846.21

Gu, L., Massman, W. J., Leuning, R., Pallardy, S. G., Meyers, T., Hanson, P. J., Riggs, J. S., Hosman, K. P., and Yang, B. (2012). The fundamental equation of eddy covariance and its application in flux measurements. Agric. For. Meteorol., 152: 135–148. https://doi.org/10.1016/J.AGRFORMET.2011.09.014

Harris, D. C. (2010). Charles David Keeling and the Story of Atmospheric CO_2 Measurements. Anal. Chem., 82(19): 7865–7870. https://doi.org/10.1021/ac1001492

Jia, X., Dukes, M. D., and Jacobs, J. M. (2009). Bahiagrass crop coefficients from eddy correlation measurements in central Florida. Irrig. Sci., 28(1): 5–15. https://doi.org/10.1007/s00271-009-0176-x

Liang, S., and Wang, J. (2020). Estimate of vegetation production of terrestrial ecosystem. In S. Liang & J. Wang (Eds.), Advanced Remote Sensing (2nd ed.). Academic Press. https://doi.org/10.1016/B978-0-12-815826-5.00015-5

Mahrer, Y., and Rytwo, G. (1991). Modelling and measuring evapotranspiration in a daily drip irrigated cotton field. Irrig. Sci., 12(1): 13–20.

Metzger, J., Nied, M., Corsmeier, U., Kleffmann, J., and Kottmeier, C. (2018). Dead Sea evaporation by eddy covariance measurements vs. aerodynamic, energy budget, Priestley–Taylor, and Penman estimates. Hydrol. Earth Syst. Sci., 22(2): 1135–1155. https://doi.org/10.5194/hess-22-1135-2018

Mizutani, K. (1997). Applicability of the eddy correlation method to measure sensible heat transfer to forest under rainfall conditions. Agric. For. Meteorol., 86(3–4): 193–203. https://doi.org/10.1016/S0168-1923(97)00012-9

Monteith, J. L., and Unsworth, M. H. (2013). Micrometeorology: (i) Turbulent Transfer, Profiles, and Fluxes. In M. H. U. John L. Monteith (Ed.), Principles of Environmental Physics (4th ed., pp. 289–320). Academic Press. https://doi.org/10.1016/B978-0-12-386910-4.00016-0

Moore, P. (2015). Should We Celebrate Carbon Dioxide ? The Global Warming Policy Foundation. http://www.thegwpf.org/patrick-moore-should-we-celebrate-carbon-dioxide/

Moorhead, J. E. (2018). Field-Scale Estimation of Evapotranspiration, Advanced Evapotranspiration Methods and Applications. Daniel Bucur, IntechOpen. https://doi.org/DOI: 10.5772/intechopen.80945

Moss, D. N. (1962). The Limiting Carbon Dioxide Concentration for Photosynthesis. Nature, 4017: 587–588.

Nisbet, E. (2007). Cinderella science. Nature, 450 (7171): 789–790. https://doi.org/10.1038/450789a

Odi-Lara, M., Campos, I., Neale, C., Ortega-Farías, S., Poblete-Echeverría, C., Balbontín, C., and Calera, A. (2016). Estimating Evapotranspiration of an Apple Orchard Using a Remote Sensing-Based Soil Water Balance. Remote Sens., 8(3): 253. https://doi.org/10.3390/rs8030253

Otero, A., Berger, A. G., Morales, X., and Calistro, R. (2015). Eddy Covariance Estimates of Evapotranspiration in Irrigated and Rainfed Soybean in Uruguay. Agrociencia, 19(3): 8. https://doi.org/10.2477/VOL19ISS3PP8

Stern, R. (2018). Early Ripening of Lychee by Heating: Using geothermal water in the Hula Valley area. Israel Agricultural Technology & Innovations Hub. https://israelagri.com/early-ripening-of-lychee-by-heating/

Tans, P., and Keeling, R. (2022). Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases. Scripps Institution of Oceanography. https://gml.noaa.gov/ccgg/trends/data.html

Wohlfahrt, G., and Gu, L. (2015). The many meanings of gross photosynthesis and their implication for photosynthesis research from leaf to globe. Plant. Cell Environ., 38(12): 2500–2507. https://doi.org/10.1111/pce.12569