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CO_2 Footprint of Kiwi Fruits Deduced from Field Measurements and Cultivation Energy Data

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Abstract: The unequivocal understanding of the planetary-global climate change has rendered the apportionment of sources and sinks of greenhouse gases in the terrestrial domain, an urgent priority. In the present study, the micrometeorological method of "dynamic gradient fluxes" coupled with the Monin–Obukhov similarity theory, was utilised for the determination of net ecosystem exchange of carbon dioxide (CO_2) from a kiwi plantation. This annual net exchange, in conjunction with the energy and fertiliser equivalent CO_2 used, established the CO_2 footprint of the produce. For the year 2023, the CO_2 Net Ecosystem Exchange (NEE) is −16.20 tonnes per hectare per year (CO_2 uptake by the plantation). The cultivation processes used throughout the year consumed +2.96 tonnes per hectare per year, and after deduction of this value from the NEE, the result is in a net CO_2 sink for the kiwi plantation of −13.24 tonnes per hectare per year. It is hence obvious that, under these conditions, the kiwi plantations in Greece can be net CO_2 sinks. This result is of increasing importance since the country is the fourth largest producer of kiwi globally, with production increasing in later years.

Keywords: CO_2 footprint; net ecosystem exchange; dynamic gradient method; kiwi plantation; CO_2 fluxes

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1. Introduction

Climate change was predicted in the 19th century, but it was brought to public attention around 50 years ago [1]. Global warming, which effects it is confirmed by data series from a large number of terrestrial and ocean meteorological stations [2]. Also, we confirmed the warming in our area based on data from the past 50 years [3].The long-living atmospheric gases and aerosol that are responsible for the greenhouse effect and hence global warming are named greenhouse gases (GHGs). The global average concentration of the most prominent of these gases, carbon dioxide (hereafter denoted as CO_2), methane (hereafter denoted as CH_4) and nitrous oxide (hereafter denoted as N_2O), has increased, non-linearly, since the onset of the Industrial Revolution. Concerning the increase in the global concentration of CO_2, this is apportioned between anthropogenic activities and natural environment sources and sinks. The European Union Regulation 2018/841 [4] sets out the ways to calculate greenhouse gas emissions and sinks from land use, land use change, and forestry (LULUCF), along with Council Decision (EU) 2016/1841 of the 5 October 2016 on the conclusion of the Paris Agreement, adopted under the United Nations Framework Convention on Climate Change, and the IPCC 2021, Report on Climate Change "The Scientific Evidence" [5,6]. The regulation specifically states in Article 7 that there should be an "*Accounting of managed arable land, managed grassland, and managed wetlands*", where: "*Each Member State shall account for greenhouse gas emissions and removals from managed crop land as emissions and removals in the periods from 2021 to 2025 and from 2026 to 2030, minus the value obtained by multiplying by five, the Member State's average annual emissions and removals resulting from managed crop land in the base period from 2005 to 2009*". In addition to the regulatory obligations of the state, above, there is also the commercial side of the issue where the knowledge of the net carbon balance (emissions minus absorptions or vice versa) may increase the market value of a product. Furthermore, the production process may, "in principle", give an incentive to the producer to reduce the effects of climate change. In a growing season, the net carbon balance for a product is determined by the micrometeorological method's measurements of carbon emission and absorption from the plants (as CO_2), and the calculations of carbon emissions from the use of fuels, fertilizers, and insecticides/herbicides for the period. This is how the carbon footprint of the product is calculated after year/s long data acquisition and processing. The difficulty in these calculations is the accurate measurement of the CO_2 mass balance (absorption versus emission) in the cultivation of the product, for which precise and accurate measuring instrumentation and proper management of the results are needed. However, an accurate determination is not possible in most countries due to a lack of data, resulting in calculating such balances with algorithms. Besides, the guiding methodology is provided by the ISO 14067 [7]. For example, paragraph 6.3.5 notes 2 of ISO 14067: "*Crop-specific data refer to greenhouse gas emissions (GHGs) determined through direct monitoring, stoichiometry, mass balance, or similar methods, and activity data i.e., inputs and outputs of cultivation processes resulting in emissions or subtractions of GHGs, or emission factors. Data for a particular crop can be collected from that crop's cultivation field or can be averaged from all crops (in the same area) that follow procedures common to all of them*". The appropriate measuring tools in this case are the micrometeorological methods of eddy covariance or dynamic gradient fluxes. The flux calculations with either of these methods, and by following the guidelines of ISO 14067, the carbon footprint of the products can be accurately and consistently calculated. The long-term monitoring of production processes will pave the way for the issue of ISO 14067 thereby increasing the commercial value of the producer's product. We have long-term field experience with both micrometeorological methods and, more specifically, the dynamic gradient fluxes method (hereafter denoted as DGF) [8,9]. The net ecosystem exchange (NEE) of CO_2 and water vapour (hereafter denoted as H_2O) of an agricultural cultivation may be determined via the calculation of ecosystem emissions due to respiration processes, i.e., Gross Ecosystem Exchange (ECORESP) minus its Gross Primary Productivity (GROSSPP), both necessitating a diverse suite of instrumentation. It is also scientifically proven that the direct determination of fluxes of energies from or to a cultivated land proves the accuracy of the DGF method in determining the NEE of the CO_2 [10–13].

Concerning the CO_2 uptake or emission from kiwi plantations, the specifics of the fluxes from enclosed orchards used in New Zealand, do not apply to the open plantation arrangements of Southern Europe [10,14]. For Southern European plantations, the climate, irrigation, and the energy use conditions differ from country to country and from year to year [15–17]. In the present study, the DGF method was used to directly determine the exchanges of energy and mass of CO_2 between the kiwi plantation and the atmosphere. The positive NEE values represent net CO_2 emissions to the atmosphere and the negative values represent the CO_2 amount sequestered from the atmosphere, according to the atmospheric science convention. The present experimental work is the first that will provide a CO_2 footprint for kiwi fruits in Eastern Mediterranean countries like Greece, based on actual micrometeorological measurements and not on "life cycle assessment" modelling. The data were collected for nine months and linearly interpolated to a year.

2. Materials and Methods

2.1. Site Description

Measurements were carried out in a typical Mediterranean kiwi orchard at Chrysoupolis (40°56′53.26″ N, 24°40′42.75″ E, approximately 11 m a.s.l.) during the 2023 growing season. The sampling site is in the northeastern part of Greece and is about 8 km from the coast. The area has a minor influence from anthropogenic sources, since the nearest town of 8885 inhabitants is 3.5 km away. The neighbouring delta of the Nestos River is 6 km away, and in the surrounding area of the sampling site, there are only agricultural activities. The rows are oriented in the northeast direction with 4 m between plants and 3.7 m between rows. It is irrigated during the dry season through a flooding system. The flux footprint for the duration of the experimental season was constantly calculated using the method of Cormann and Meixner [18].

2.2. Experimental Setup

The instrumentation was installed on a 5 m micrometeorological tower at three different heights above the ground (2.5 m, 3.7 m, and 4.6 m). This system consisted of instruments used to determine the vertical profiles of horizontal wind speed (WS, ms^{-1}), air temperature (T, °C), relative humidity (RH, %) and CO_2 concentrations (CO_2, ppmv).

Three 2D Ultrasonic Anemometers (model 4.3880.00.000, Thies-CLIMA, Adolf Thies GmbH & Co. KG, 37083 Göttingen, Germany) were positioned at the same heights as the Compact Hygro-Thermo Transmitters, model 1.1005.64.173 (ThiesCLIMA, Adolf Thies GmbH & Co. KG, 37083 Göttingen, Germany) in their radiation shields.

At each of these heights (2.5 m, 3.7 m, 4.6 m), inlets of sampling tubing were also installed. These three tubings were connected to a valve control box (constructed in the laboratory), housed in a weather-proof enclosure near the base of the mast. The valve control box consisted of four threeway Galtek Solenoid Operated Diaphragm Valves (Entegris, Inc., Billerica, MA 01821, USA). The outlet of the valve control box was connected to the inlet of an Infrared Gas Sensor, Gascard NG for CO_2 (0–1000 ppmv parts per million by volume) (Edinburgh Instruments Ltd., Livingston EH54 7DQ, UK), which used a pump (model SP 100 SA-VD 230V/50Hz 7s09046, Schwartzer Precision GmbH, 45141 Essen, Germany) connected to its outlet. The sampling cycle of the valve control box was synchronised to the sampling time of the CO_2 analyser. To determine the vertical profile of CO_2 concentrations, sequential concentration measurements between the three heights were conducted (every 10 min). The suitability of such a system for the determination of gradient flux measurements has been confirmed in the literature [19].

Data from all instruments were sent to two ADAM-4017 data acquisition modules (Advantech Co., Ltd., Blue Ash, OH 45241, USA) and analysed using the DASYLAB V13.00.0 software program (Measurement Computing Corporation, Norton, MA 02766, USA) installed on an industrial computer (model ARK-2121LSYS, Advantech Co., Ltd., Blue Ash, OH 45241, USA). A RS485 to RS232 converter (ADAM 4520, Advantech Co., Ltd., Blue Ash, OH 45241, USA) was used to establish communication between the ADAM-4017 modules and the computer.

The main meteorological variables were measured with an Atmos-41 weather station (METER Group GmbH, 81379 München, Germany) and logged on ZL6 data logger (METER Group GmbH, 81379 München, Germany) every 10 min. For example, incoming solar radiation (Q, Wm^{-2}), air temperature (T, °C), wind speed (WS, ms^{-1}), wind direction (wd, degrees), relative humidity (RH, %), precipitation (PCP, mm), and barometric pressure (P, kPa) were recorded. In addition, the soil moisture was monitored at -10 cm depth with an EC-5 Soil Moisture Probe (METER Group GmbH, 81379 München, Germany).

Flux-gradient data were acquired at 1 Hz and averaged every 40 min. Real-time monitoring of the instrumentation and daily data collection were achieved with a 4G router (model TP-LINK Archer MR200, COSMOTE S.A., 67100 Xanthi, Greece) connected to the remote office computer.

2.3. The Dynamic Gradient Flux Method

The method used for the determination of CO_2 flux densities in the present study has been described extensively in our previous publications [8,9] and in the free electronic literature at the website https://docs.neanias.eu/en/latest, under the section "Atmospheric services—A1 ATMOFLUD", which is our contribution to the EU project "NEANIAS" (accessed on 19 October 2024).

2.4. Indirect CO_2 Emissions Calculations

While direct CO_2 emissions were calculated as described above, this study includes the CO_2 emissions during the production of applied fertilisers and chelated calcium, as well as the operation of machinery at the kiwi orchard. Table 1 shows the annual direct CO_2 emissions from fertilisers, chelated calcium, diesel in tractor, and electricity for irrigation purposes.

Table 1. Direct CO_2 emissions of consumables used in the kiwi orchard annually.

Consumable	Direct CO_2 Emissions (kg CO_2)	References
Fertiliser 12-8-16	522.1	[20]
Fertiliser 8-10-34	222.7	Ditto
Chelated calcium	6.6	Ditto
Diesel and tractor use	126.3	https://www.feace.com/single-post/the-carbon-footprint-of-diesel-generators (accessed on the 19 October 2024)
Electricity	602.3	Greece: 394 gr CO_2/kWh https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-15#tab-chart_7 (accessed on 15 October 2024)

2.5. Energy Budget

From the acquired data, sensible and latent heat fluxes were determined using the DGF method. Hence, the energy balance closure was used to evaluate the accuracy of the determination flux densities of CO_2. In the literature, deviations of about 20–30% from closure are commonly observed in surface energy budget measurements. This is due to the energy storage of the ground and the foliage. The energy balance equation is as follows:

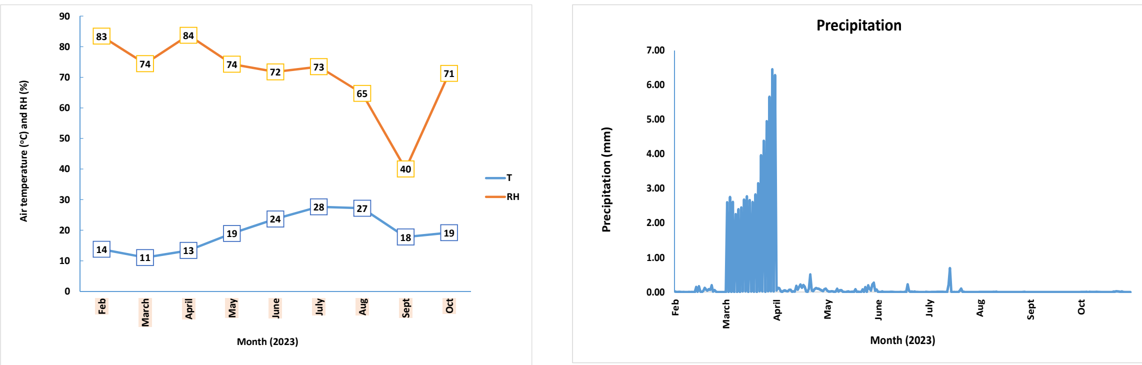
$$Q = QH + QE + G, \quad (1)$$

where Q is the net all-wave radiation, QH and QE are the respective turbulent fluxes of sensible and latent heat, and G is the net change in heat storage within the ground and the foliage, down to a level where heat exchanges become negligible. An equivalent example for cities is described in the literature [8].

3. Results

3.1. Meteorological Conditions

Figure 1a depicts the mean RH and air temperature, and Figure 1b the respective values of precipitation for each month during 2023.



(**a**) (**b**)

Figure 1. Mean monthly RH and T at 2.5 m (**a**); mean monthly precipitation (**b**).

Year 2023 was a dry year, as Figure 2b confirms. The annual rainfall level for the area during 1971–2000 was 513.61 mm (http://climatlas.hnms.gr/sdi/; accessed on the 1 October 2024). For the year 2023, the same region had a rainfall level of 442.4 mm (http://emy.gr/emy/en/climatology; accessed on the 1 October 2024). However, irrigation was affected by flood irrigation with water extracted from a nearby gravity-fed channel with water originating from the nearby river Nestos.

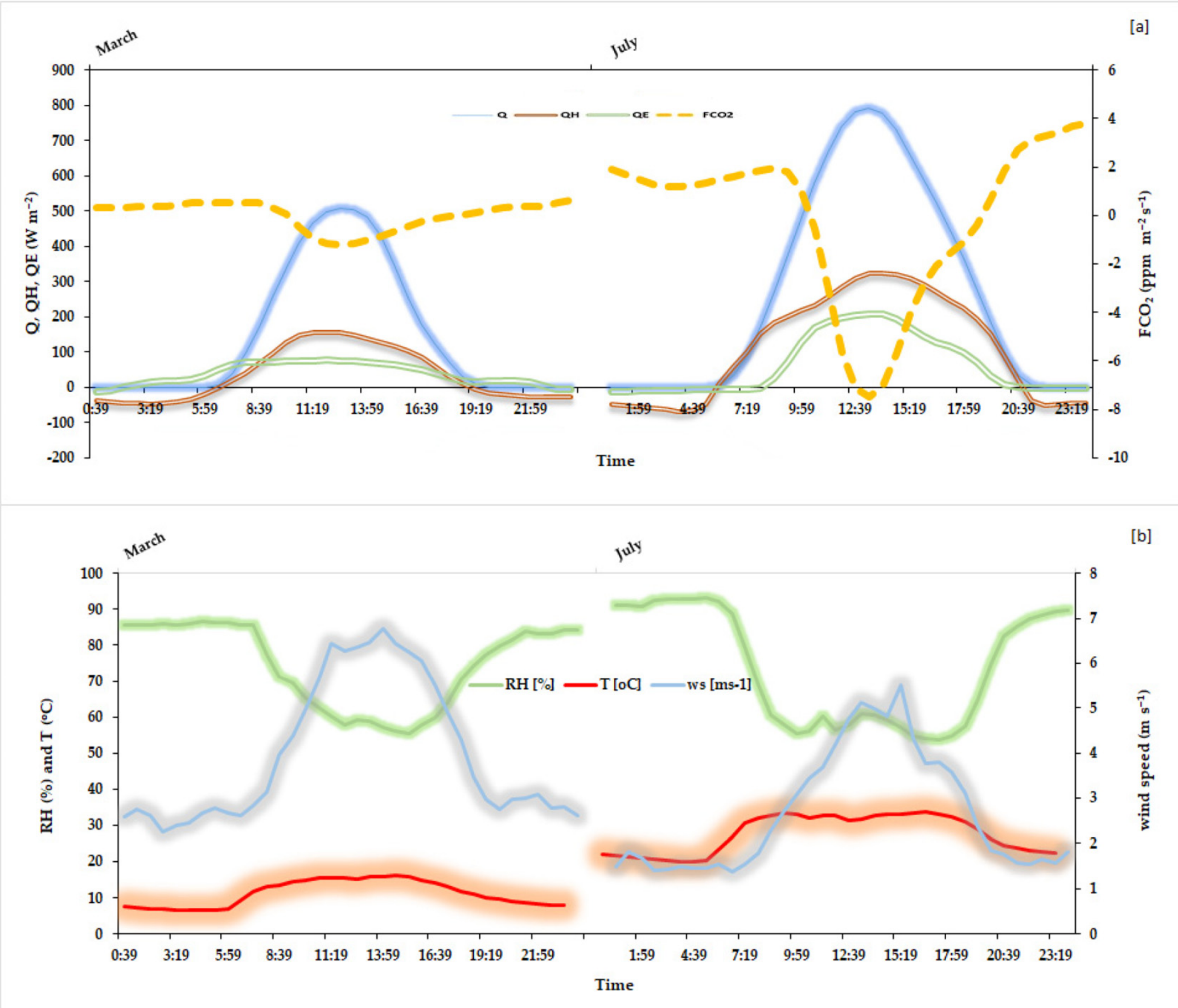


Figure 2. Average monthly diurnal variation of energy and CO_2 fluxes (**a**) and RH. T, WS (**b**).

3.2. Energy Fluxes and CO_2 Flux (FCO_2)

QH, QE, and FCO_2 were determined by the above-mentioned micrometeorological method. The diurnal variation of all calculated fluxes during the two months (one in winter time and one in the summertime) are compared in Figure 2a, along with the respective RH, T and WS in Figure 2b.

The scatterplot in Figure 3 presents the relationship of the sum of the heat fluxes QH + QE with the net all wave radiation Q, all experimentally observed in the field. The slope of the driven linear regression line reveals that 30% of Q is the energy storage of the ground and the foliage.

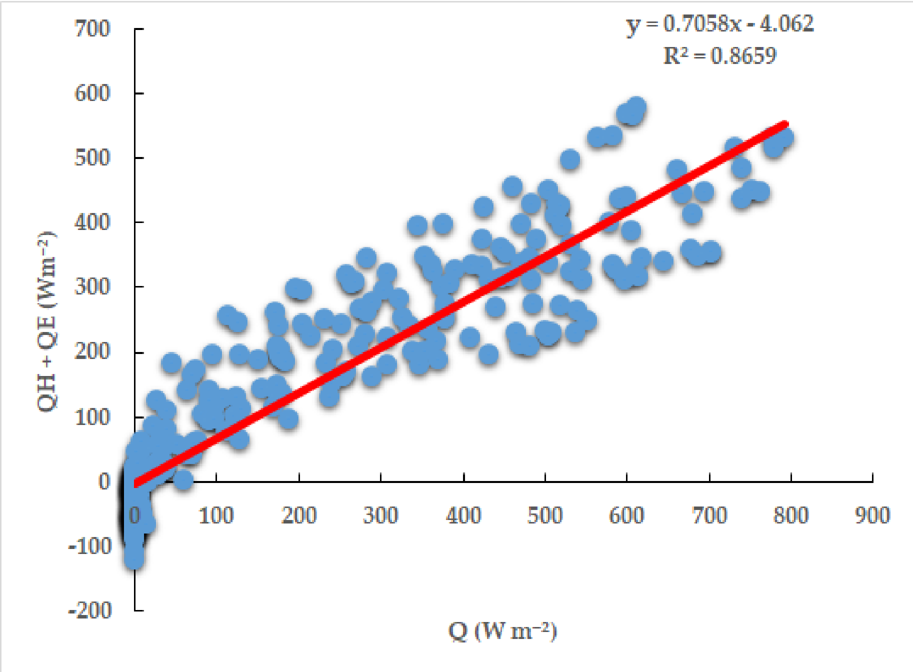


Figure 3. Heat flux densities' relationship with net-all wave radiation in the kiwi plantation at Chrysoupolis—GR (2023).

Figure 4 presents the monthly average FCO_2 experimentally determined in situ plus the estimated flux for the months of January, November, and December 2023. The final CO_2 uptake necessitated the linear interpolation method for our data to a full year, as described and used for "FLUXNET" and other literature methods [21–25].

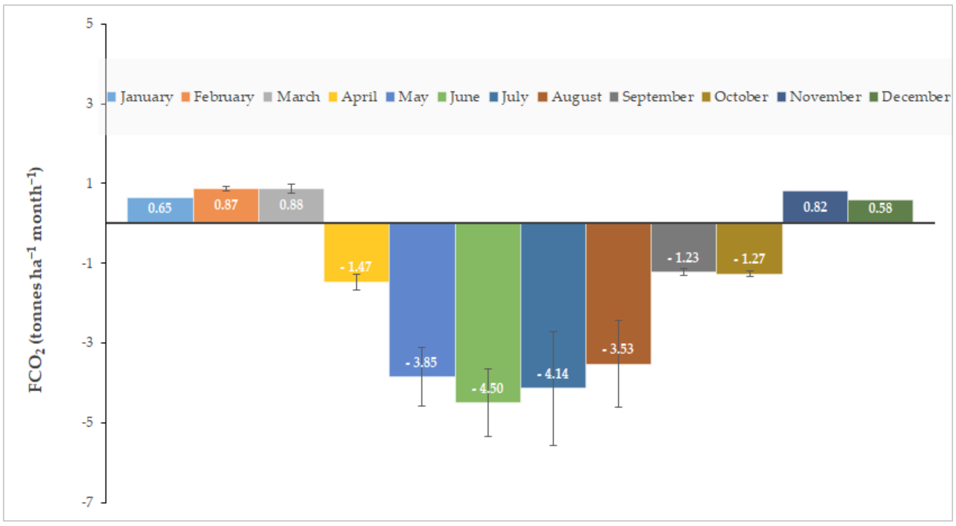


Figure 4. Monthly CO_2 flux densities (mean ± SD) in the kiwi plantation at Chrysoupolis—GR (2023).

The annual sum of the NEE for the plantation is −16.20 tonnes of CO_2, uptake/assimilation per hectare or 8.10 tonnes of CO_2 for the 0.5 hectare of the plantation size.

4. Discussion

The energy balance closure reveals that the energy storage was, on average, 30% of the net all wave radiation, thus the accuracy of the determination flux densities of CO_2 through the DGF method was validated. Without foliage and fruits, positive FCO_2 was observed, but during the growing season, negative fluxes were observed.

The subtraction of indirectly emitted CO_2 (e.g., use of diesel for field work, transport, and fertiliser production and application) from the NEE-summed annual CO_2 values, yields the CO_2 balance for the annual production of kiwi, thus determining the footprint for the production of a kilogram or tonne of kiwi (see Table 1 for indirectly accounted CO_2 emissions) [20].

In the present study, net CO_2 emissions/uptake amount to −16.20 tonnes per hectare, or −8.10 tonnes for the plantation (at the 95% confidence limit). The plantation produced 17.50 tonnes of kiwi fruit in the 2023 growing season. This translates to the assimilation of 0.463 kg of CO_2 per kg of produced kiwi fruit. The sum of required CO_2 for cultivation processes, as calculated in Table 1, is 0.084 kg CO_2 per kg of produced kiwi fruit. Subtracting this later value from the 0.463 kg of assimilated $CO_{2,}$ we have a result of a total of 0.379 kg assimilated CO_2 per kg of produced kiwi fruit. In simpler words, each kg of produced kiwi has a negative footprint of 0.379 kg CO_2. On the plantation scale, the net CO_2 uptake was (−) 6.63 tonnes for the 2023 growing season or (−) 13.24 tonnes per hectare. Comparison with the literature findings is tabulated in Table 2.

Table 2. CO_2 assimilation data for kiwi orchards.

Plantation and Variety of Kiwi Fruit	CO_2 NEE Tonnes per Hectare	Method Used (Year of Determination)	Reference
North Italy (ca. 47° North). *Actinidia deliciosa* var. "*Howard*"	−11.33	Eddy Covariance (2007)	[16]
North Italy *Actinidia deliciosa* var. "*Howard*"	−14.44	Eddy Covariance (2012)	[17]
New Zealand *Actinidia deliciosa* var. "*Howard*"	−2.40	Life Cycle Assessment (2010)	[20]
Southern Italy (ca. 40° North) *Actinidia deliciosa* var. "*Howard*"	−17.5 ton of CO_2 eq per hectare 20 year mean 17.5 × 0.9072 = 15.87 Hence −15.87 tonnes CO_2/hectare per annum.	Life Cycle Assessment (2022)	[15]
North East Greece (ca. 40° North). *Actinidia deliciosa* var. "*Howard*"	−13.24	Dynamic Gradient flux (2023)	Present work

It can be seen that our data agree with the data from kiwi orchards in similar Southern Mediterranean climates (albeit determined using LCA and based on 20 year averages). It is also apparent that even data obtained with the eddy covariance method are not distinctly different from the data of our present work.

5. Conclusions

We used the DGF micro-meteorological method for the annual observation and determination of CO_2 and H_2O fluxes over a kiwi orchard in northeast Greece. The sequential sampling of the conservative CO_2 at three different heights and the simultaneous sampling of H_2O resulted in robust data (at the 95% confidence interval) as proved by the energy balance method. This proves the validity of the "old" method, which, for the average plantation manager, is financially viable to use at a cost of less than EUR 10,000. The year 2023 was a relatively dry year, but the plantation was flood-irrigated. After subtracting the CO_2 emissions for the cultivation management processes from the NEE of the CO_2 assimilation by the plantation, one reaches a negative footprint of 0.379 kg of CO_2 per kg of produced kiwi fruit. This value, of course, is plantation- and year-specific, but it is indicative of the rest of the plantations in the area as a directly determined footprint estimation. The results are important for Greek kiwi producers, since this cultivation is constantly increases in numbers and tonnage (https://www.zim.com/fr/zim-blog/the-greek-kiwifruit-harvest-kicks-off; accessed on 15 October 2024). However, the two caveats concerning the endeavour of these field determinations are as follows: firstly, the specialised personnel necessary to set up, record, and process the data acquired; secondly, the perennial problem of dealing with missing data during the year. On a positive note, specialised personnel are seriously needed in the new era of the production of agricultural products for the food industry.

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