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RESEARCH ARTICLE

Net Ecosystem Annual Budget of Carbon Dioxide in a Mediterranean Vineyard

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Abstract

The current study determined the net ecosystem exchange of carbon dioxide (CO_2) from a young vineyard of the" Merlot" variety, using the micrometeorological method of "Eddy Covariance". The CO_2 footprint of the produce was determined using the above method for the annual net exchange of CO_2 from the plantation, as well as the equivalent CO_2 emissions for the viticulture processes. According to the determination of the plantation's CO_2 assimilation, the annual CO_2 Net Ecosystem Exchange (NEE) for 2023 was -6,356 kg CO_2 per hectare. The annual consumption of 4,287 equivalent kg CO_2 per hectare by the farming methods was also estimated. After deducting this annual 4,287 kg of CO_2 per hectare from the NEE, the annual vine plantation's net CO_2 sink is −2,069 kg per hectare. This also translates to a Carbon Footprint (CF) of -0.213 kg of CO_2 per produced kg of "Merlot" grapes, for the year 2023. Therefore, it is clear that in this case the young vineyard of "Merlot" in northeastern Greece acts as a net CO_2 sink for the season 2023. These results may introduce the incentive to study further, in the country, other varieties of grape and under different climatic conditions, soil composition and irrigation

Keywords: CO_2 Footprint, Net Ecosystem Exchange, Eddy Covariance, Vineyard Plantation, CO_2 Fluxes.

1. Introduction

One manifestation of the Global Climate Change (GCC) is the warming of the lower atmosphere, confirmed by long term data series from a large number of terrestrial and ocean meteorological stations [1,2]. For reasons of simplicity, this global warming is reported as "mean annual increase in the temperature of the lower atmosphere of the earth". The warming for Greece is also confirmed by data from 10 airport meteorological stations for the past 50 years [3]. Long-living Green-House Gases (GHGs) and aerosol, for example, carbon dioxide (CO_2), methane (CH_4) nitrous oxide (N_2O) and aerosol black Carbon (BC) are responsible for the greenhouse effect and hence global warming. The global average concentration of the most prominent of these gases, CO_2, has increased, non-linearly, since the onset of the Industrial Revolution [1,2]. This increase is apportioned between anthropogenic activities and natural environment sources and sinks. Concerning the agricultural economic sector, the apportionment is based on a number of calculating algorithms, rarely verified or not, by real measurements. The European Union Regulation 2018/842 [4] refers to EU Regulation 2018/841 and both refer to the earlier regulation 529/2013 for the original algorithms of the accounting rules on greenhouse gas emissions and removals relating to land use, land-use change and

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forestry (LULUCF) [5,6]. A maximum quantity of 280 million tons of CO_2 equivalent of those removals is divided among Member States and included in the above Regulations as an additional possibility for Member States to meet their CO_2 emissions commitments, when and if needed.

Apart from the previously mentioned state legal obligations, there is also the business side of the issue, where a product's market value may increase if the net carbon balance—that is, emissions less absorptions or vice versa—is accurately determined. Hence, "in principle," the cultivating process can motivate the producer to mitigate the consequences of climate change. The net carbon balance for a product for a growing season is determined by the micrometeorological method measurements of carbon emission and absorption from plants (as CO_2) and the addition/subtraction of carbon emissions from the use of fuels, fertilizers, and insecticides/herbicides for each annual cycle.

Accurately determining, by measurements, the CO_2 mass balance (absorption/assimilation against emission) during the product cultivation, is challenging, in these calculations, requiring precise and accurate measuring equipment as well as sophisticated data treatment. However, due to lack of data, most countries are unable to make exact determinations of carbon footprint of their agricultural products. Hence, algorithms are used to calculate these balances/footprints. The necessity of accuracy is described in the guiding methodology provided by the ISO 14067 [7]. The most commonly used measuring methods in this case are the eddy covariance or the dynamic gradient, micrometeorological techniques. By following the ISO 14067 requirements and employing for example, the eddy covariance method, the flux calculations may accurately and consistently determine the products' carbon footprint. The long-term monitoring of the cultivation processes will increase the product's economic value and enable the issue of ISO 14067.

Hence, the eddy covariance method (henceforth referred to as EC) is extensively used in the field, determines directly a cultivation's net ecosystem exchange (NEE) of CO_2 and water vapor (H_2O) and not only [8]. Also, an agricultural cultivation's (NEE) of CO_2 and H_2O can be calculated by subtracting its ecosystem emissions resulting from respiration processes (ECORESP) minus its Gross Primary Productivity (GROSSPP), both necessitating a diverse suite of instrumentation [8,9]. The EC is simpler, proven and not involving other instrumentation [8,9]. In this way, in determining the NEE of a vineyard by EC or another micrometeorological method, simply, one takes into account all parameters of the "vineyard ecosystem" that contribute to the calculation of its CO_2 footprint. Minus, of course, the CO_2 used for the viticulture (fuel, water, electricity, fertilisers, pesticides/fungicides in CO_2 equivalents). The accounting of the CO_2 footprint only by Life Cycle Assessment (LCA) methods, does not account for the plant's ecosystem contribution to this determination [8-10].

The global agriculture sector emitted 17 Gt CO_2 eq. in 2019 [11]. In 2019, Greece's agricultural emissions accounted for approx. 7,875 kt CO_2 eq. [12]. Furthermore, agriculture is one of the sectors that is expected to be most severely affected by climate change [13].

As far as the viticulture and viniculture in Greece, the Greek Statistical authority in its 2020 census, reports that the combined economic sectors occupy 102,934.90 hectares of cultivated land [14]. However, in the "STATE OF THE WORLD VINE AND WINE SECTOR IN 2022", report of the International Organisation of Vine and Wine (OIV), Greece is reported to occupy ca. 7-10 times less agricultural viticulture land than the rest of the Southern European countries which in any case are at that top the world [15].

There exist only a limited number of studies concerning viticulture that take into account the NEE of the studied homestead [5 publications]. These publications have proven the necessity of utilising the NEE in determining the CO_2 footprint of the produce as well as the CO_2 from the cultivation processes using LCA calculations. But not LCA alone/only. Furthermore, they have proven the ability of the viticulture systems to act as a significant sink of CO_2, far larger than the CO_2 equivalents of the materials used for the cultivation processes, hence rendering the LCA alone calculations inaccurate.

The aim of the present study is to focus on the direct measurement of the NEE of a young vineyard at the 42 North Parallel and the climate conditions of North East Greece. The NEE will be determined by utilising the EC method. Together with the LCA of the materials used (as CO_2 equivalents), for the cultivation processes of "Merlot" young vines, the CO_2 footprint of the produced grapes will be determined.

2. Materials and Methods

2.1 Site Description

Measurements were conducted in a typical Mediterranean young vineyard of the Merlot variety at Mangana (station at UTM zone 35 T; 320634 E and 4537472 E, approximately 10m a.s.l.). These started in January 2023 to cover the 2023 growing season. The site is in the northeastern part of Greece and is about 6 km from the coast. The area has a minor effect from anthropogenic sources because the nearest city of 70,873 habitants is at a distance of 18.5 km away in the North direction (6^o). The neighboring delta of Nestos River is at a distance of 10 km and in the surrounding area of the sampling site there exist only agricultural activities. The selected site ensures a homogeneous fetch, fulfilling the criteria for the ECF methodology.

The (0.9-hectares) vineyard was planted in 2017 with grapevines of the "Merlot" variety. The rest of the 1.3 hectares of the site South of the local agricultural road was planted with new vine seedlings. The site of the 1.5 hectares north of the service road were planted with the Cabernet Sauvignon vines. The rows are oriented in the north to south direction (see also figure 3 of the WPLOT for 2023), with 1.20 m between plants and 2.85 m between rows. The soil is characterized as "sandy clay loam". It is irrigated during the dry season through a drip system once a week and during prolonged high temperatures and dry spells, twice a week, in both cases for twelve hours. The fertilization was carried out on the 5th of March 2023.

The average canopy height was approximately 1.50 m. The ECF sonic anemometer and sampling inlet were positioned 3.5 m above this height and within the inertial sublayer where the turbulence is fully developed, and the effect of surface features is blended. Furthermore, it was placed at an approximate distance of 120 m from the North and North-East corners of the site for "sampling" the appropriate vineyard footprint. The rest of the south field of 1.3 hectares, was either arid or planted with new seedlings.

Figure 1. *Micrometeorological eddy-covariance station at the Mangana "Merlot" vineyard (Eastern Macedonia and Thrace, Greece; Mercator zone 35 T; 320634 E and 4537472 N).Also, the CNR4 and logging and ground-based instrumentation are shown.*

2.2 Experimental Set up

The vineyard net ecosystem exchange (NEE vin) was measured during the whole study period applying the eddy covariance (EC) method. This technique allows for long-term monitoring of vegetation-atmosphere exchanges at the ecosystem scale, providing spatially and temporally averaged, dry carbon dioxide, water vapor and sensible heat fluxes every 30 min. The 5m-mast was deployed in the monitoring area and was equipped with a CSAT3 directional sonic anemometer (Campbell Scientific Ltd., Loughborough, UK) and a closed-path EC system at its base (Picarro G-2311-f; PICARRO, Inc., 95054 Santa Clara, USA). The directional sonic anemometer was positioned at a height of 3.5 m above the canopy and was oriented to the northeast due to the local prevailing wind direction (see also WPLOT for 2023 in figure 3). The fast-response virtual temperature (Tv) and the three-dimensional wind vectors were measured with the CSAT3 at 10 Hz. The Picarro Analyzer determined dry CO_2 and water vapor concentration utilizing wavelength-scanned cavity ringdown spectroscopy (WS-CRDS). A 6-m Bev-A-Line XX Tubing (I.D. 1/4" and O.D. 3/8", 88682, Salem, OPTUBUS GmbH) was used for air sampling at a height of 3.5 m above the canopy with its inlet near the mid-point of the sonic anemometer path. This tubing and an external vacuum pump (model MD 4 NT, VACUUBRAND

GMBH+CO KG, 97877, Wertheim, DE) were connected to the Picarro Analyzer. The net all wavelength radiation at the site was determined via a four-component CNR4 radiometer (Kipp & Zonen, 2628 Delft, NL), mounted 3 m above the canopy level.

Data from all instruments were logged on a CR3000 datalogger (Campbell Scientific Ltd., Loughborough, UK) and stored at a computer using the Logger Net software (Campbell Scientific Ltd., Loughborough, UK). Real time monitoring of the instrumentation and daily data collection were achieved with a 4G router (model ZTE MF296R, COSMOTE S.A., 67100 Xanthi, GR) connected to the laboratory computer. Meteorological data of barometric pressure and precipitation were obtained from the neighbouring micrometeorological station near Chrysoupolis, which was at a distance of 18 km away Eastward (260^o).

2.3 Preparation and Post-Processing of the Data

The local prevailing wind direction was from the north or northeast. The sonic anemometer data that corresponded to wind directions from 150° to 330° were excluded from further analysis. Data linked with values of horizontal mean wind speed less than 1.0ms^{-1} were also rejected. Three or more consecutive missing values were replaced by linear interpolation.

As a brief reference to the ECF, carbon dioxide fluxes as well as the momentum, sensible and latent heat fluxes were computed using the mean covariance time-averaged statistics. Sensible (QH) and latent heat (QE) flux densities [W m^{-2}] were estimated utilizing the following equations.

$$Q_H\ [\mathrm{W\ m^{-2}}] = \rho\ Cp\ \overline{w'\theta'}, \quad (1)$$

$$Q_E\ [\mathrm{W\ m^{-2}}] = \lambda\ \overline{w'q'}, \quad (2)$$

where Cp is the specific heat of the air, λ is the latent heat of vaporization, ρ is air density and w´, θ´, q´ are the turbulent fluctuations of the vertical component of the wind velocity, virtual potential temperature, and water vapor concentration respectively. Turbulent fluctuations were computed as the difference between instantaneous and mean scalar quantities.

Carbon dioxide and momentum flux densities were calculated from EC data as

$$F_{CO2}[\mathrm{mg\ m^{-2}\ s^{-1}}] = \overline{w'c'}, \quad (3)$$

$$F_{mom}\ [\mathrm{kg\ m^{-1}\ s^{-2}}] = \rho\ \overline{w'u'}, \quad (4)$$

where c´ is the turbulent fluctuation of the CO_2 concentration. Generally, the flux density of CO_2 above a surface is the mean of the variation of the vertical wind velocity in ms^{-1} times the mean variation of the concentration of CO_2 in mg m^{-3} resulting in a flux density of mg m^{-2} s^{-1}.

To determine friction velocity u*[ms^{-1}] and Monin-Obukhov length L the following formulas were used.

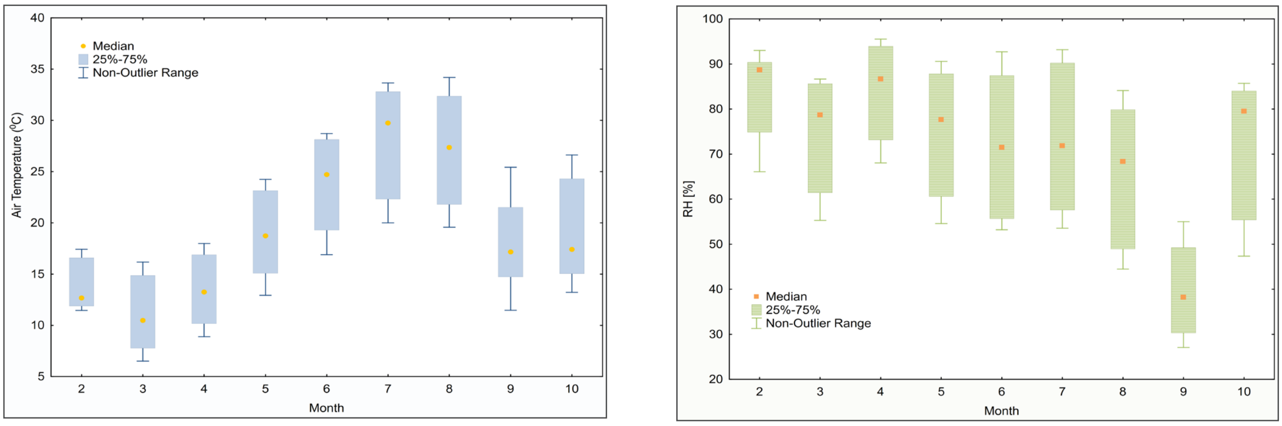
$$u^*[\mathrm{ms^{-1}}] = [\overline{u'w'}^2 + \overline{v'w'}^2]^{1/4}, \quad (5)$$

$$L = -\frac{u_*^3}{k\frac{g}{\theta}\overline{w'\theta'}}, \quad (6)$$

However, flux density data were post-processed via a code written by us in MATLAB 10 and translated to “PYTHON”. The code is a freeware available under the section “Atmospheric services—A1 ATMOFLUD”; our contribution to the EU project “NEANIAS” [16] . The corrections made to the closed-path eddy covariance measurements include the following: (1) correction for time delay (constant time lag), (2) data cleaning (range constraints), (3) de-spiking (for a series of moving windows of various lengths according to Vickers and Mahrt [17]), (4) gap filling (linear interpolation), (5) coordinate rotation (2-d coordinate rotation or planar fit method), (6) detrending (block averaging over 30-min periods), footprint analysis [18-19], quality control (steady state test according to Foken and Wichura [20]). However, all data treatment, procedure details and corrections are published, using our own code in one of our recent publication [10].

3. Results

Figures 2 and 3 depict meteorological data for the area and for the recorded months of 2023. They are a guidance for more frequent drip irrigation in the months June to September. Figure 4 depicts an example of the cumulative diurnal variation of the determined fluxes of Sensible, Latent heats and the net all wavelength radiation for the month of August 2023 as well as CO_2 fluxes. While Figure 5 depicts the statistics of the heat fluxes indicating that the important parameter in the growing evolution of the plantation is Q.



(a) **(b)**

Figure 2. *(**a**) Monthly statistics of air temperature (2023); (**b**) of Relative Humidity (2023) from our nearby Chrysoupolis meteorological station applicable also to the vineyard site*

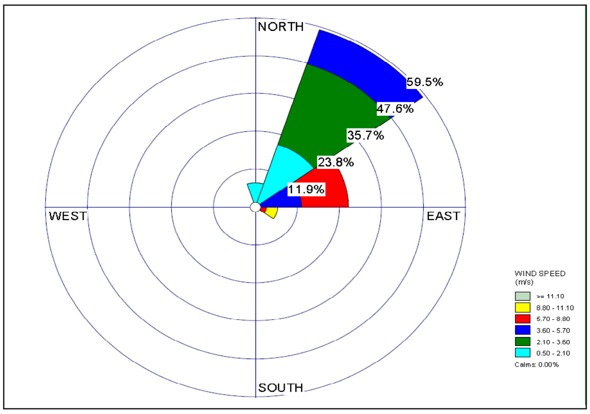


Figure 3. *Wind rose for the year 2023 at the Mangana site, based on the horizontal vector of the sonic anemometer data*

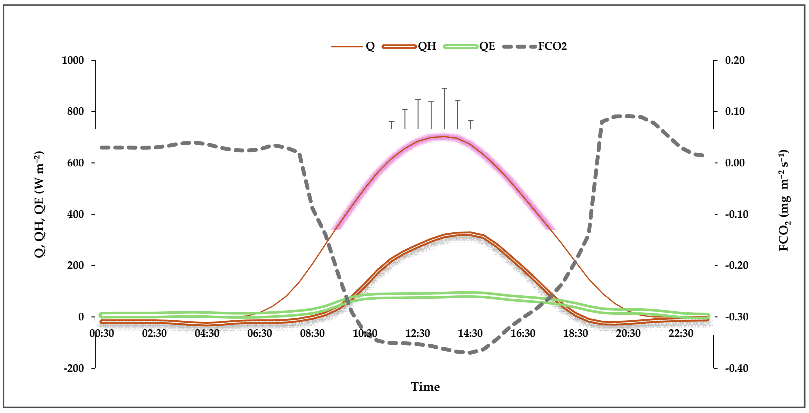


Figure 4. *Mean values of the diurnal variation of the net all wavelength radiation, sensible, latent heat fluxes and CO_2 flux during August 2023 are presented. Standard deviations for Q ranged from 35 to 320 W m-2*

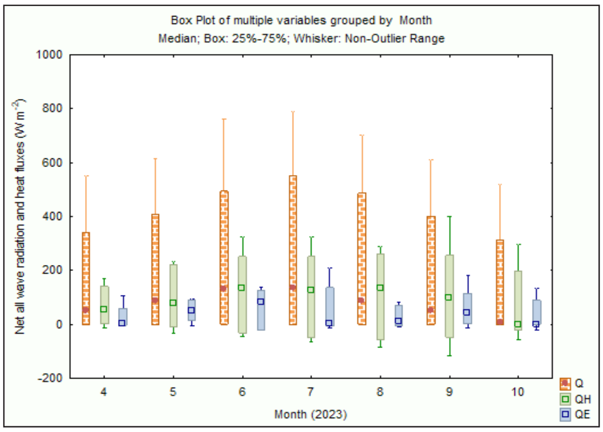


Figure 5. *Mean values and standard deviations of the heat fluxes for the Mangana station where QH= Sensible heat flux, QH= Latent heat flux and Q=Net all wave radiation.*

Table 1 records the cultivation materials and energy equivalents of CO2 used for the 12-month 2023 season. Total 4,763 kg of CO2 for 9,000 m2 which translates to 144.32 g C m-2, for cultivation processes annually.

Table 1. *Direct CO2 emissions of consumables used in the "Merlot" vineyard annually.*

Consumable	Direct CO_2 emissions (kg CO_2)	References
Fertilizer 14-8-18	2,700	[21,22]
Pesticides	0.27	[21,22]
Diesel and tractor use (480 lt) at 2.45 ± 0.35 kg/lt	1,176	https://natural-resources.canada.ca/sites/nrcan/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_9_e.pdf (accessed 22 March 2025).
Electricity Greece: 394 gr CO_2/kWh	887.0	https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-15#tab-chart_7 (accessed 22 March 2025).

As depicted in Figure 6, the determined NEE for the Mangana "Merlot" vineyard was -214.35 g C m^{-2} y^{-1} OR -784.66 g CO_2 m^{-2} y^{-1} OR -7.85 kg CO_2 m^{-2} y^{-1} OR -7,062 kg CO_2 assimilated in the 9,000 m^2 of vineyard. To this we add (in absolute numbers we subtract) 4,763 kg of CO_2 used for the cultivation processes of for 9,000 m^2 vineyard as shown in Table 1. Thence, the total assimilated CO_2 for the vineyard was -2,300 kg CO_2. As mentioned in the methods section the vineyard produced 1200 kg of grape per 1000 m^2, hence the total produce was 10,800 kg. This in turn translates to -0.213 kg CO_2 assimilated for each kg of grape. In other words, there was a negative footprint of 213 g of CO_2 per kg of "Merlot" grapes produced in "our" vineyard.

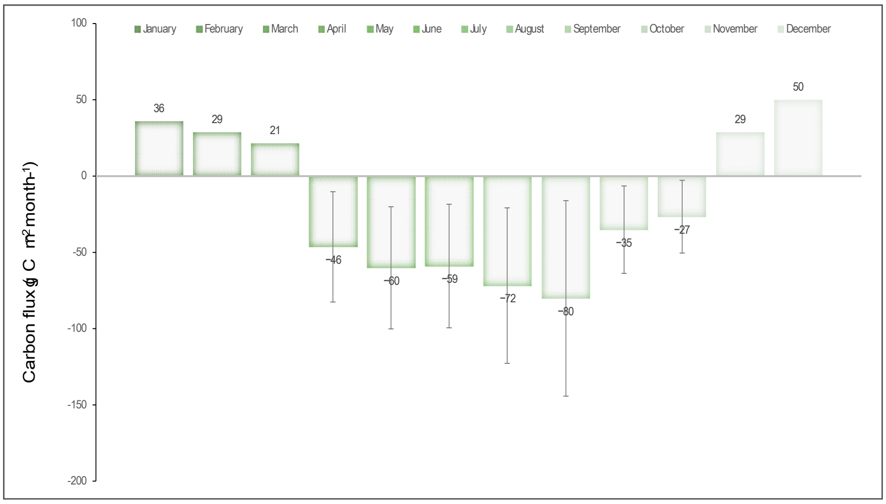


Figure 6. *CO_2 fluxes as C (monthly mean ± SD) for the year 2023.*

4. Discussion

The young vineyard producing "Merlot" type of grape, was monitored for the production year of 2023. Its set up is described in the methods section together with the observation instruments used. The prevailing wind was as expected from the North East, with no large or small urban center, or highway, upwind. All measurements and data obtained were filtered so as to include the vineyard observations, based on the footprint calculations of the Kormann and Meixner methodology which is presented as a freeware by Neftel A. et. al. [18,19]. All meteorological conditions were typical for the area for the production year, of course bearing in mind the "Global Change" conditions [13].

In determining the CO_2 footprint of an agricultural product, one has to take into account the Net Ecosystem Exchange of CO_2 during the cultivation process as depicted in Figure 6. This fact has been well documented in the literature [8,22] as well as in our previous publications [10,16]. The calculation of the CO_2 equivalent of all materials used in the cultivation processes is also necessary as listed in Table 1. However, the later alone does not provide the correct Carbon Footprint (CF) of the product. Hence, our results can only be compared with the "correct" published results that take into account the NEE of the Plantation. These are tabulated in Table 2. We have converted our fluxes and those of the literature to the same units, for comparison reasons.

Table 2. *Net Ecosystem Exchange in vineyards (average values derived with EC).*

Location	NEE g C m^{-2} y^{-1}	References
Wuwei, Gansu Province, China (for three years)	-820 to -961	[23]
South Sardinia, Italy	-195	[9]
Negrisia di Ponte di Piave, Italy	-814	[24]
North Eastern Italy (for three years)	-69 to -207 -134 (average for three years)	[25]
Castiglione in Teverina, Italy	-150 (50th percentile)	[26]
Caldaro, South Tyrol, Italy	-246 (± 54) [1]	[27]
non-irrigated grassed (Nevidzany village, Slovak Republic)	-97 [2]	[28]
Mangana (Greece)	-214	Present study

[1] growing season, (mid-April to mid-November). [2] growing season, (April-September).

Although there exist and are practiced a number of methods to establish the NEE of an agricultural product plantation [8], micrometeorological methods are direct and well established. Furthermore, are simple to implement, provided that the correct screening of the results is applied. The eddy covariance method that we use, does encompass a number of data filters and limitations as recorded in our previous projects and publications [e.g. 10,16]. We can hence directly determine the annual NEE of the CO_2 for the aforementioned plantation. By subtracting the equivalent CO_2 used for the materials and processes during the annual cycle of cultivation, one determines the actual CF for the plantation and hence the CF per kilogram of grape produced. These data are depicted in Figure 6 and Table 1.

Our data are unique for this type of cultivation in Greece and can only be compared with Italian and Spanish cultivations due to similarities in geographical latitude and Mediterranean climate as in Table 2. There are of course differences in the determined CF that depend on the year, type of vine, its age and cultivation methods, but the similarities are obvious.

Hence, in the present work we stress the importance and necessity of taking into account the NEE of CO_2 for CF calculations of individual agricultural products. These individual, per product determinations of CF may present a mosaic of CF for an area, but still informative. They can be also used to offset a country's CO_2 emission obligations. The CF determination (not an LCA assessment) of the agricultural production of the whole of a country is a different matter.

5. Conclusions

We have determined, using actual field data the CF of CO_2 for a vineyard of the "Merlot" variety. The results are given in CO_2 assimilated per kg of grapes which in this case is -0.213 kg of CO_2 per kg of "Merlot" grapes for the year 2023. Our results are similar to other cultivations in the area, bearing in mind the similarities in the Mediterranean climate, geographical latitude and terrestrial conditions.

We further emphasized the necessity to include the NEE in these determinations as well as the fact that these should be determined/measured in the field.

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